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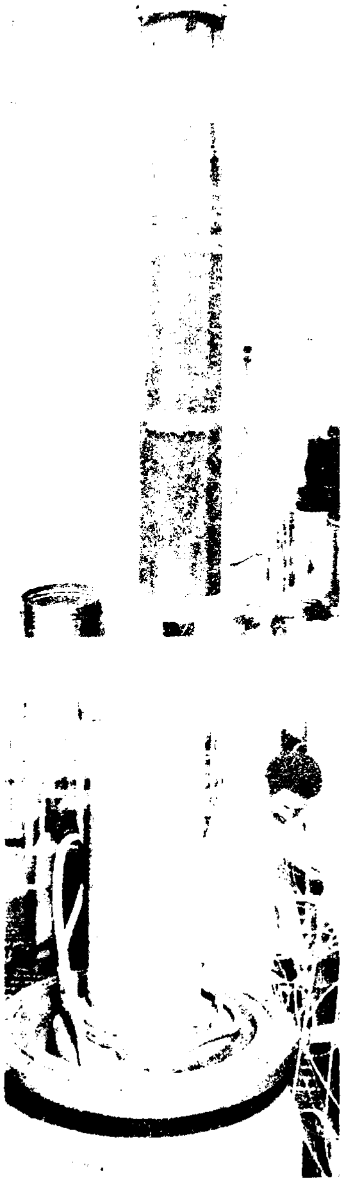

COMPACTION CONTROL OF EARTH-ROCK MIXTURES: HOW TO DEVELOP AND USE DENSITY INTERFERENCE COEFFICIENTS AND OPTIMUM WATER CONTENT FACTORS

by

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13. ABSTRACT *(Maximum 200 words)*
This report provides instructions for the development and application of a new compaction control or quality assurance procedure for soils containing gravel-sized particles. The method is based on Density Interference Coefficients which relate the maximum dry density of the total gradation to those of its minus 3/4-in. or minus No. 4 fraction and on Optimum Water Content Factors which relate the optimum water content of the total gradation to those of its minus 3/4-in. or minus No. 4 fraction. Entire families of gradations of earth-rock mixtures such as would typically be obtained from a single borrow source can be represented by single curves of the two parameters versus gravel content. A short-cut method to obtain the curves over the entire range of gravel content of the total materials without large-scale compaction testing of the total materials is described. Instructions are provided as to how to calculate maximum dry density and optimum water content to be associated with the fill density sample from the values of Density Interference Coefficient and Optimum Water Content Factor.

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PREFACE

This report provides instructions for the development and application of a new compaction control or quality assurance procedure for soils containing gravel-sized particles. Funding for the research leading to development of the new method was provided by the Headquarters, US Army Corps of Engineers (USACE), under the designation of Civil Works Research and Development (CWRD) Work Unit No. 32342, entitled "Testing Large-Particled Soils." The Technical Monitor for this work unit is Mr. Richard F. Davidson, Directorate of Civil Works, Engineering Division, Geotechnical and Materials Branch, Soils Section, USACE, Washington, DC. The CWRD Materials-Soils program manager is Mr. G. P. Hale, Chief, Soils Research Center (SRC), Soil and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS.

This report was prepared by Dr. Victor H. Torrey III, Soil Mechanics Branch (SMB), S&RMD, under the general supervision of Mr. Milton M. Meyers, Chief SMB, Dr. Don C. Banks, Chief, S&RMD, and Dr. William F. Marcuson III, Chief, GL.

The laboratory research testing program leading to development of the new compaction control method described herein was under the direct supervision of Mr. Robert T. Donaghe of the Soils Research Facility, SRC, S&RMD. Technical editing and coordination of preparation of this report for publication were performed by Mrs. Joyce H. Walker of the WES Visual Production Center, Information Technology Laboratory.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic inches	16.38706	cubic centimetres
Fahrenheit degrees	*	Celsius degrees
feet	0.3048	metres
foot-pounds (force)	1.355818	metre-newtons or joules
inches	2.54	centimetres
pounds (force)	4.448222	newtons
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square inches	6.4516	square centimetres

* To convert temperature in degrees Fahrenheit (F) to degrees Celsius (C), use the following formula: $C = (5/9)(F-32)$.

COMPACTION CONTROL OF EARTH-ROCK MIXTURES: HOW TO DEVELOP AND USE DENSITY INTERFERENCE COEFFICIENTS AND OPTIMUM WATER CONTENT FACTORS

PART I: INTRODUCTION

Background

1. Laboratory tests to obtain moisture-density relationships for soils containing large particles, i.e., earth-rock mixtures, have been both problematical and questionable over the years. The problem in dealing with such materials arises from the fact that, if the full-scale gradation is to be tested, the size of the laboratory test specimen must be sufficiently large to assure assessment of the properties and/or behavior of the mixture. There seems to be general, although informal, agreement within the profession in this country that the ratio of test specimen diameter to largest particle size should be no less than 5 or 6 to achieve a good test on the mixture. Both the US Army Corps of Engineers (USACE 1970) and the American Society for Testing and Materials (ASTM 1991a and 1991b) compaction test methods conform to this concept. Working with a ratio of 5 or 6 leads to what would be conventionally considered large test specimens (in excess of 6 in. in diameter) when the largest particle size begins to exceed 1 in. Testing of larger specimens entails the need for larger and more expensive laboratory hardware, higher capacity compaction and/or loading mechanisms, special processing and handling equipment, more spacious facilities, and lots of hard manual labor. Therefore, beginning years ago, as one laboratory after another began to encounter these realities in testing soils containing large particles, methods were developed or adopted on faith which were believed to provide adequate estimates of full-scale gradation properties but which also circumvented testing of large specimens of the full-scale materials. Simplistically, the avoidance procedures have included practices such as discarding the larger particles (scalping), or scalping and then replacing the "oversized" fraction with an equal portion by weight of manageable sizes, or even the creation of a "parallel" gradation with a smaller maximum particle size. Formal research to assess the reliability of these methodologies for testing earth-rock mixtures

has been very sporadic and has mostly fallen to organizations engaged in regular major design and construction activities involving these materials such as the USACE, US Bureau of Reclamation (USBR), and some state agencies (including universities). However, because of the expense, time consuming nature of the work, and the many variables commensurate with earth-rock mixture research, sporadic efforts have not sufficed to eliminate many of the basic questions.

2. In consideration of the scale of the problems in the laboratory environment, it is no surprise that earth-rock mixtures also present many challenges in the field construction environment. Of course, the field laboratory faces the testing uncertainties previously mentioned. Next comes the requirement for an accurate, efficient method for determining the as-compacted fill density and fill water content of soils containing large particles. Then, there is the need to compare those values of fill density and water content to appropriate values of maximum dry density and optimum water content to assure that specifications are met, i.e., a quality control or assurance procedure. Because of the rate of fill placement economically necessary in the construction of large fills, it is not feasible to expect to develop complete moisture-density curves for samples of earth-rock mixtures from each fill density test location. Additionally, a larger fill density test specimen is required in these materials which translates to greater time and effort per test and fewer tests per work shift. So, it is imperative that the compaction control methodology not only be shortcut in nature but also sufficiently accurate to confirm the specified attributes of the fill.

3. Several versions of compaction control techniques have been utilized by the USACE over the years in dealing with earth-rock mixtures. Fill density tests using direct and/or indirect methods (USACE 1977, paragraph 5-10) and water content determinations on the total sample have been ordinarily used to obtain the as-compacted parameters, but the specifications themselves or the means of relating the as-compacted values to the specifications have generally avoided dealing with the full-scale materials. For example, the specified range for water content and the value of minimum desired percent compaction may be based on the optimum water content and maximum dry density for a fraction of the total material (say, minus 3/4-in.* fraction). In the field, the

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* A table of factors for converting non-SI to SI (metric) units of measurement is presented on page 3.

maximum dry density and optimum water content for the fraction may be determined using the one- or two-point control procedure (USACE 1977, Appendix B). Then, the dry density and water content of the fill sample of the total material are corrected for the percent "oversize" (percent of total material by weight larger than 3/4 in.) to obtain the dry density and water content of that fraction for comparison to the maximum dry density and optimum water content of that fraction. A similar but reversed approach would be to correct the maximum dry density and optimum water content of the fraction for the percent "oversize" to estimate those parameters for the total material and then compare the fill density test results on the total material to those values.

4. Recent research by Torrey and Donaghe (1991a and 1991b) provides a thorough examination of current compaction control practices and shows that there is potential for considerable error in those procedures. A new and more precise method of compaction control or quality assurance has been developed out of those studies which still retains the advantage of avoidance of or, at least, greatly reduced large-scale compaction testing of the total materials. The new method introduces two new parameters termed the Density Interference Coefficient I_c and the Optimum Water Content Factor F_{opt} which relate maximum dry densities and optimum water contents of fractions to those of the parent total materials on the basis of percent gravel in the total materials.

Purposes

5. The purpose of this report is to provide instructions concerning the development of curves relating values of the Density Interference Coefficient and Optimum Water Content Factor to percent by weight of gravel in earth-rock mixtures. In addition, the use of these curves in controlling or assuring the quality of compacted fills composed of such gravelly soils will be explained.

PART II: BASIC CONCEPTS AND DEFINITIONS

Earth-Rock Mixture

6. The methods to be explained herein are applicable to soils containing gravel up to 3 in. in maximum particle size and sufficient clay* or silt fines (minus No. 200 sieve fraction) to exhibit typical moisture-density compaction curves by which values of maximum dry density and corresponding optimum water content are defined. The methods may also be applicable to materials containing cobble sizes (larger than 3-in. diam) but too little confirming data are available for such gradations to generally include them.

Oversized and Finer Fractions

7. The term "oversized fraction" originates from the compaction control or quality assurance procedures which are based on the compacted state of a fraction of the total material. Laboratory compaction tests which can be considered conventional in the Federal, state and private sectors employ either a 4-in. diam mold for material passing the No. 4 sieve or a 6-in. diam mold for material passing the 3/4-in. sieve. The USACE has also more recently adopted a 12-in. diam mold test for earth-rock mixtures passing the 2-in. sieve (USACE 1970, Appendix VIa) but that large-scale test is not considered conventional for the general definitions given here. In addressing materials which contained sufficiently large gravel fractions which could not be scalped (discarded) according to prescribed test procedures, the term "oversized fraction" came into use to refer to that fraction of the total material consisting of particle sizes too large to be included in the selected conventional compaction test. That fraction has also been sometimes referred to as the "coarser fraction." Thus, if the 4-in. mold test is selected, the oversized fraction is the plus No. 4 fraction and, if the 6-in. mold test is preferred, the oversized fraction becomes the plus 3/4-in. material. The "finer fraction" then refers to that material employed in the compaction test, i.e., the minus No. 4 or minus 3/4-in. fraction. For example, Figure 1 shows a typical earth-rock gradation. It is seen from Figure 1 that the oversized (coarser)

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* Soil classification is by the Unified Soil Classification System.

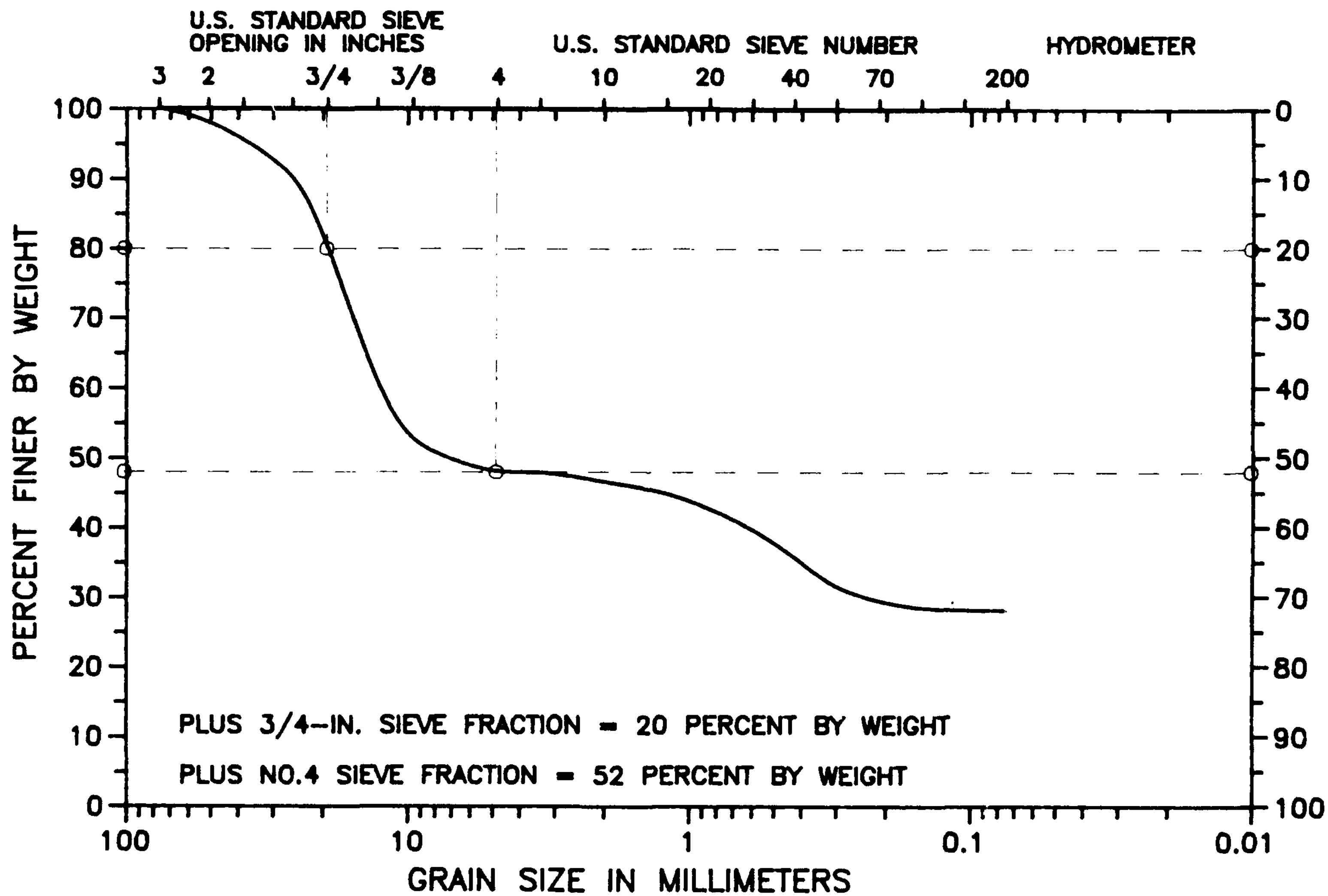


Figure 1. Percent oversize relative to minus 3/4-in. and minus No. 4 fractions

fraction c with respect to compaction testing in the 6-in. diam mold (plus 3/4-in. fraction) is 20 percent by weight and the finer fraction f or minus 3/4-in. fraction is, therefore, 80 percent by weight. Likewise, with respect to compaction testing in the 4-in. diam mold, the oversized fraction c is the plus No. 4 fraction which is the same as the gravel content or 52 percent by weight and the finer fraction f becomes 48 percent by weight.

Dry Density of the Total Material Versus Corresponding Dry Density of the Finer Fraction

8. Given an earth-rock mixture which has been compacted to some dry density γ_t , it is possible to derive an expression which relates γ_t to that of a finer fraction γ_f contained within it. The expression as originally derived by Ziegler (1948) is cited in USACE (1977), Appendix B, and is as follows:

$$\gamma_t = \frac{\gamma_f \gamma_w G_m}{f \gamma_w G_m + c \gamma_f} \tag{1}$$

where

γ_t = dry density of the total material, pcf

γ_f = dry density of the finer fraction, pcf

γ_w = unit weight of water, 62.4 pcf

G_m = bulk specific gravity of oversized particles, dimensionless (see USACE 1970, Appendix IV)

f = percent finer fraction by weight expressed as a decimal

c = percent oversized fraction by weight expressed as a decimal

This relationship is valid as long as the finer fraction completely fills the voids between the particles of the oversized fraction. If the minus No. 4 fraction is taken as the finer fraction, there is no reason to be concerned about this restriction as long as the gravel content (plus No. 4 fraction) remains less than about 60 percent by weight. It is desirable for purposes of these instructions to rearrange Equation 1 to solve for the density of the finer fraction γ_f in terms of the density of the total material γ_t as follows:

$$\gamma_f = \frac{f\gamma_t\gamma_w G_m}{\gamma_w G_m - c\gamma_t} \tag{1a}$$

Water Content of the Total Material Versus Corresponding Water Contents of the Oversized and Finer Fractions

9. The water content of the total material can be calculated as the weighted sum of the water contents of the oversized and finer fractions as follows:

$$W_t = fW_f + cW_c \tag{2}$$

where

W_t = water content of the total material, percent

W_f = water content of the finer fraction, percent

W_c = water content of the oversized fraction, percent

f = percent finer fraction by weight expressed as a decimal

c = percent oversized fraction by weight expressed as a decimal

This equation is also given in USACE (1977), Appendix B, except that the absorption A of the oversized fraction is substituted for the water content of the oversized fraction W_c. The absorption A is defined as the saturated surface-dry water content of a gravel although it is not defined or discussed in the USACE laboratory soils testing manual (USACE 1970). However, the absorption may be calculated from the values of bulk and apparent specific gravities (see USACE 1970, Appendix IV) as follows:

$$A = \frac{G_a - G_m}{G_a G_m} \times 100\ percent \tag{3}$$

The water content of the oversized fraction in the total material may or may not be equivalent to its absorption. This assumption has been made because the water content of the gravel within the total material will not vary

significantly and will be a much lower value than that of the finer fraction and near the value of the absorption. However, because specified ranges in placement water content for earth-rock mixtures may only be 3 to 4 percentage points, a small error in water content of the gravel may produce a significant error in water content of the total material calculated from Equation 2 at higher gravel contents. It is not practical to determine the gravel water content for every fill sample during construction. However, a better procedure compared with just assuming the absorption is provided as Appendix A to this report. The method of Appendix A can be used during design of the project or early in construction to determine a value for water content of the gravel for general use. In this manner, the fill water content for the total fill density sample can be calculated from the corresponding fill water content of the finer fraction of the fill density sample using Equation 2. This procedure would avoid the need for large ovens in the field laboratory for drying of the total fill density sample.

Maximum Dry Density of the Total Material Versus Maximum Dry Density of the Finer Fraction

10. If the value of the maximum dry density of the finer fraction γ_{fmax} is substituted in Equation 1 above there is no reason to expect that the calculated value of dry density for the total material γ_t will equal the maximum dry density of that total material. Stating it in a converse manner, if the total material is compacted to its maximum dry density, there is no reason to expect that the finer fraction within it is also always brought to its maximum dry density. So, when the total material is at its maximum dry density γ_{tmax}, the finer fraction within it exists at some percent R_c of its maximum dry density γ_{fmax}. R_c is then the percent compaction of the finer fraction when the total material is at its maximum dry density γ_{tmax}. Therefore, the dry density of the finer fraction γ_f can be expressed as follows:

$$\gamma_f = R_c \gamma_{fmax} \tag{4}$$

Research has shown that the percent compaction of the finer fraction R_c when the total material is at its maximum dry density γ_{tmax} varies with percent

gravel P_g in the total material, i.e., percent plus No. 4. If the correct value of R_c is known for the given total material along with the maximum dry density of the finer fraction γ_{fmax}, the equivalent expression for γ_f of Equation 4 can be substituted into Equation 1 to calculate the correct value for the maximum dry density of the total material γ_{tmax}. That substitution yields the following equation:

$$\gamma_{tmax} = \frac{R_c \gamma_{fmax} \gamma_w G_m}{f \gamma_w G_m + R_c c \gamma_{fmax}} \qquad (5)$$

where

γ_{tmax} = maximum dry density of the total material, pcf

γ_{fmax} = maximum dry density of the finer fraction, pcf

γ_w = unit weight of water, 62.4 pcf

G_m = bulk specific gravity of the oversized fraction

f = percent finer fraction by weight expressed as a decimal

c = percent oversized fraction by weight expressed as a decimal

R_c = percent compaction of the finer fraction expressed as a decimal when the total material is at its maximum dry density γ_{tmax}.

Optimum Water Content of the Total Material Versus Optimum Water Content of the Finer Fraction

11. Given a total material which exists at its optimum water content W_{topt}, there is no reason to expect that a finer fraction within it would be found to be at its optimum water content W_{fopt}. In fact, if increasing quantities of moist gravel are added to a given gradation of finer fraction material, the water content of the finer fraction must be steadily increased to produce the optimum water content of the total mixture. Therefore, insertion of the value of the optimum water content of the finer fraction W_{fopt} into Equation 2 above cannot be expected to generally yield a calculated value of water content of the total material W_t which is equal to the optimum water content of the total material W_{topt}. Some other means of relating W_{fopt} to W_{topt} must be devised if the optimum water content of the total material is to be correctly predicted using that of the finer fraction. The new method of

controlling compaction of earth-rock mixtures given later in this report entails such a relationship.

Density Interference Coefficient I_c

12. The Density Interference Coefficient I_c is dimensionless and defined as follows:

$$I_c = \frac{R_c}{P_g G_m} \tag{6}$$

where

R_c = percent compaction of the finer fraction expressed as a decimal when the total material is at its maximum dry density γ_{tmax}.

P_g = percent gravel (plus No. 4) in the total material expressed as a decimal.

G_m = bulk specific gravity of the gravel, dimensionless

Note that I_c may be based on either the minus 3/4-in. or the minus No. 4 fraction. If the minus No. 4 fraction is taken as the finer fraction, the percent gravel P_g is equal to the percent oversized fraction c.

13. Equation 6 can be solved for R_c in terms of I_c as follows:

$$R_c = I_c P_g G_m \tag{7}$$

Then Equation 7 for R_c can be substituted into Equation 5 to yield the following:

$$\gamma_{tmax} = \frac{I_c P_g \gamma_{fmax} \gamma_w G_m}{f\gamma_w + c I_c P_g \gamma_{fmax}} \tag{8}$$

Optimum Water Content Factor F_{opt}

14. The Optimum Water Content Factor F_{opt} is dimensionless and defined as follows:

$$F_{opt} = \frac{W_{fopt}}{P_g W_{topt}} \tag{9}$$

where

W_{fopt} = optimum water content of the finer fraction

W_{topt} = optimum water content of the total material

P_g = percent gravel (plus No. 4) in the total material expressed as a decimal.

W_{fopt} and W_{topt} may be expressed either as a percentage or as a decimal value as long as both are expressed in the same manner. As is the case for the Density Interference Coefficient I_c, the Optimum Water Content Factor F_{opt} may be based on either the minus 3/4-in. or minus No. 4 fraction.

PART III: DEVELOPING CURVES OF I_c and F_{opt} VERSUS PERCENT GRAVEL IN THE TOTAL MATERIAL

Families of Compaction Curves

15. Earth-rock gradations which derive from a single geologic formation may generally be expected to vary in gravel contents (plus No. 4 fractions), percent fines (minus No. 200 sieve fractions), and maximum particle size. As long as the materials exhibit similar gravel particle shapes by size, reasonably consistent bulk specific gravity of the gravel, gravel contents less than 35 to 40 percent, and fines which are not radically different in plasticity, compaction curves will form a family conforming relatively well to a single "line of optimums" as shown in Figure 2. In some cases, materials of the same generic family but containing gravel contents which begin to exceed about 35 percent may exhibit compaction curves which begin to fall to the dry side of the family of curves representing lower gravel contents. Torrey and Donaghe (1991a and 1991b) saw this effect in their studies of the literature for some earth-rock gradations containing only 35 percent gravel while other gradations with gravel contents exceeding 60 percent did not exhibit the tendency. Should this tendency for gradations containing higher gravel contents to deviate from the neat family represented by their cousins with lower gravel contents be observed for the materials at hand, it will not negate the new methods explained herein. In addition, all of these trends will be true regardless of the particular compactive effort employed. The very popular one- and two-point compaction control methods discussed in USACE, Appendix B, (1977) rely on separation of the materials into "families" of compaction curves. All of the instructions to follow presume that the range of the <u>finer fractions</u> of the earth-rock mixtures at hand reasonably define a single family of compaction curves. The data obtained as described below in developing curves of I_c and F_{opt} versus gravel content should indicate whether or not the <u>finer fractions</u> of the material must be divided into more than one family grouping and, therefore, corresponding additional curves of I_c and F_{opt} versus gravel content developed.

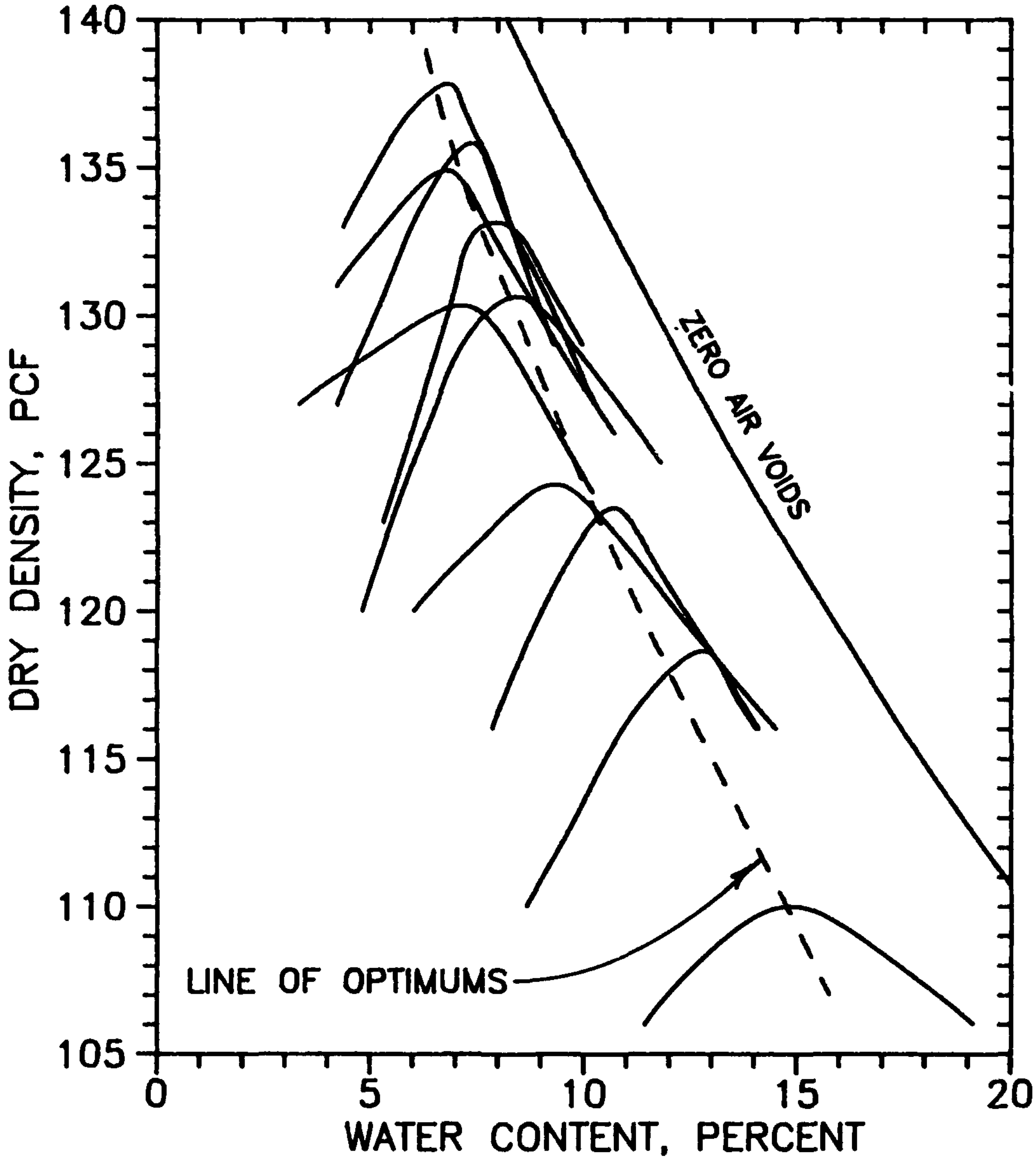


Figure 2. A typical family of compaction curves reasonably defining a single line of optimums

Density Interference Coefficient I_c Versus Gravel Content P_g

General

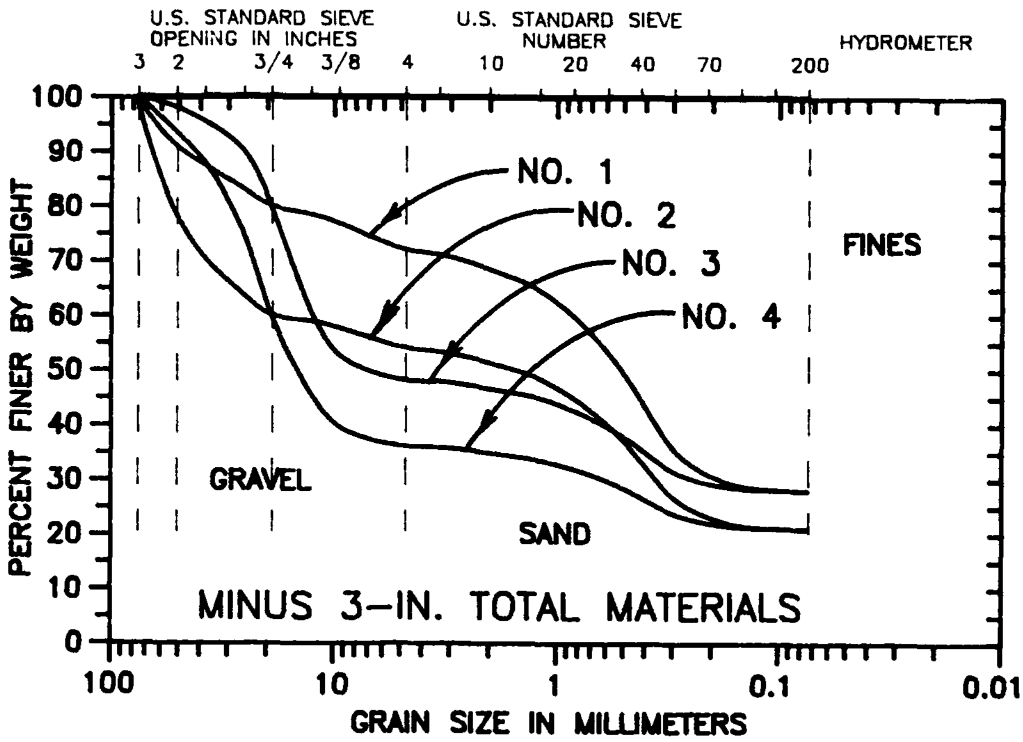
16. Developing a curve of Density Interference Coefficient I_c versus gravel content will be explained employing data derived from a range in minus 3-in. earth-rock total materials and their fractions. The importance of including fractions of the total materials in the example lies in showing that the minus 3/4-in. and minus No. 4 fractions can be used to develop the curve for the entire family of gradations without large-scale compaction testing of the total materials.

Example gradations

17. Figures 3 and 4 show examples of minus 3-in. total materials containing clay (CH) fines and their minus 2-in., minus 3/4-in., and minus No. 4 fractions. The standard effort compaction curves for these gradations are shown in Figure 2 to define a family acceptably conforming to a single line of optimums even though gravel content ranges up to 64 percent. Note that the water content scale of Figure 2 is such that the scatter among the curves is magnified. If modified compactive effort had been employed, a similar pattern would have been observed although all maximum dry densities would have been higher and all optimum water contents lower. Table 1 summarizes the pertinent fractional percentages for each gradation and their corresponding maximum dry densities and optimum water contents.

Calculating I_c

18. For the materials shown in Figures 3 and 4, each of the gradations containing gravel can be treated as if they were total materials, i.e., individual earth-rock gradations, with varying maximum particle sizes and gravel contents. For the minus 3-in. and minus 2-in. gradations, two values for I_c can be calculated since one value can be based on using the minus 3/4-in. fraction as the finer fraction and the other using the minus No. 4 fraction as the finer fraction. In addition, when the minus 3/4-in. gradation is treated as a total material, I_c can be calculated using the minus No. 4 fraction as the finer fraction. For convenience, Equation 6 is repeated as follows:



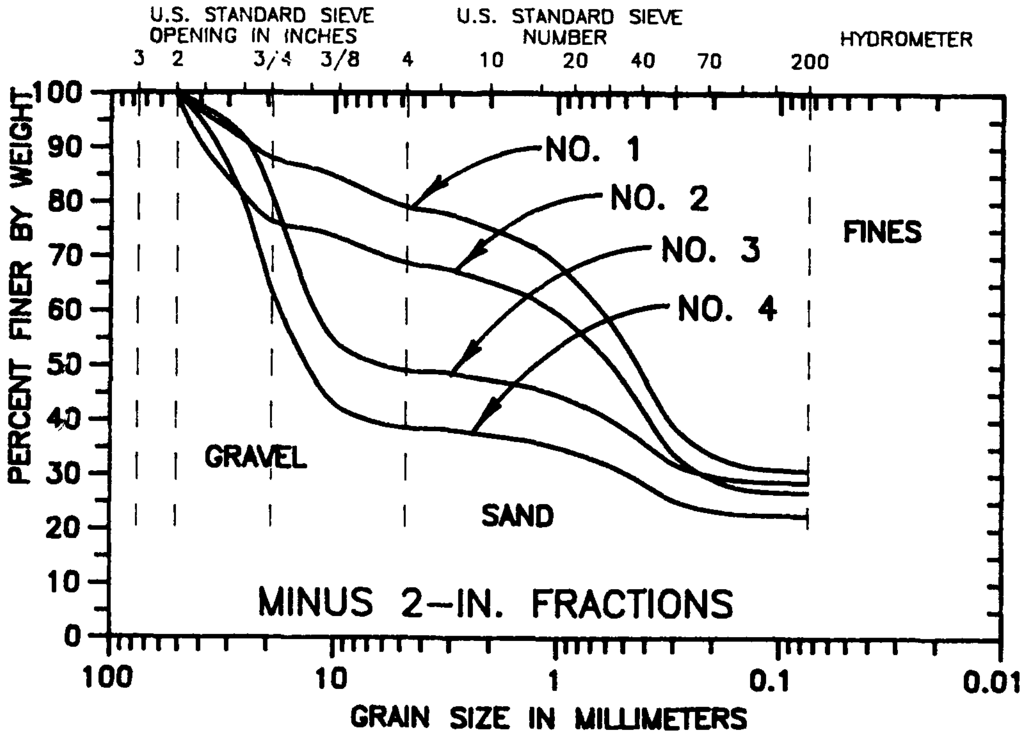
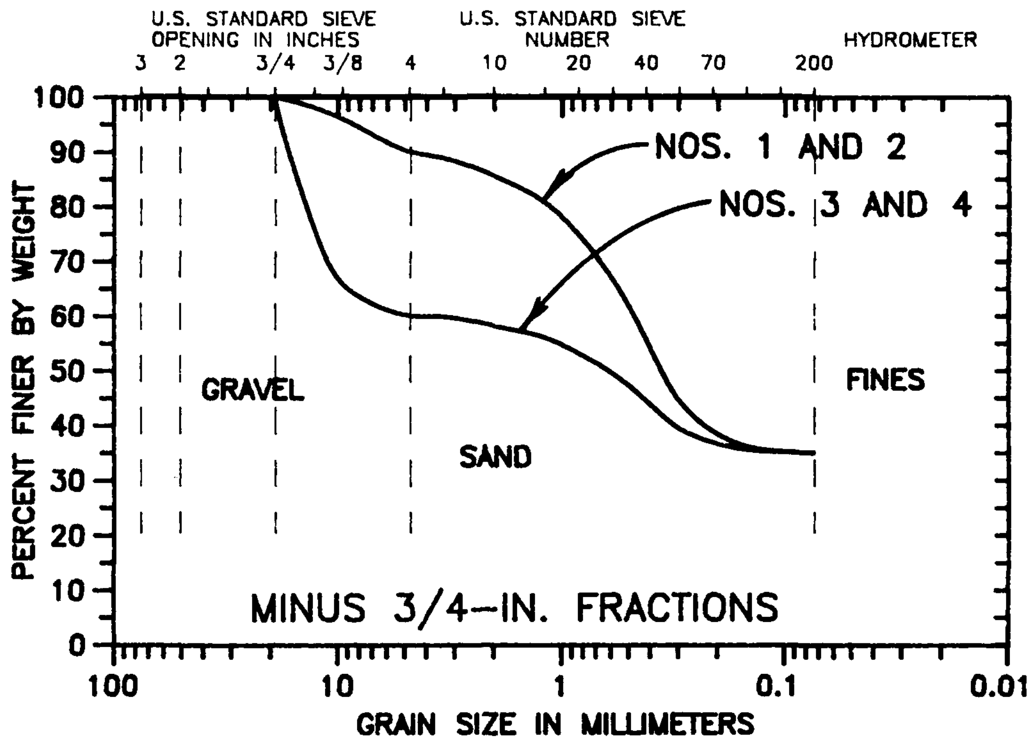


Figure 3. Example gradations, minus 3-in. total materials and their minum 2-in. fractions



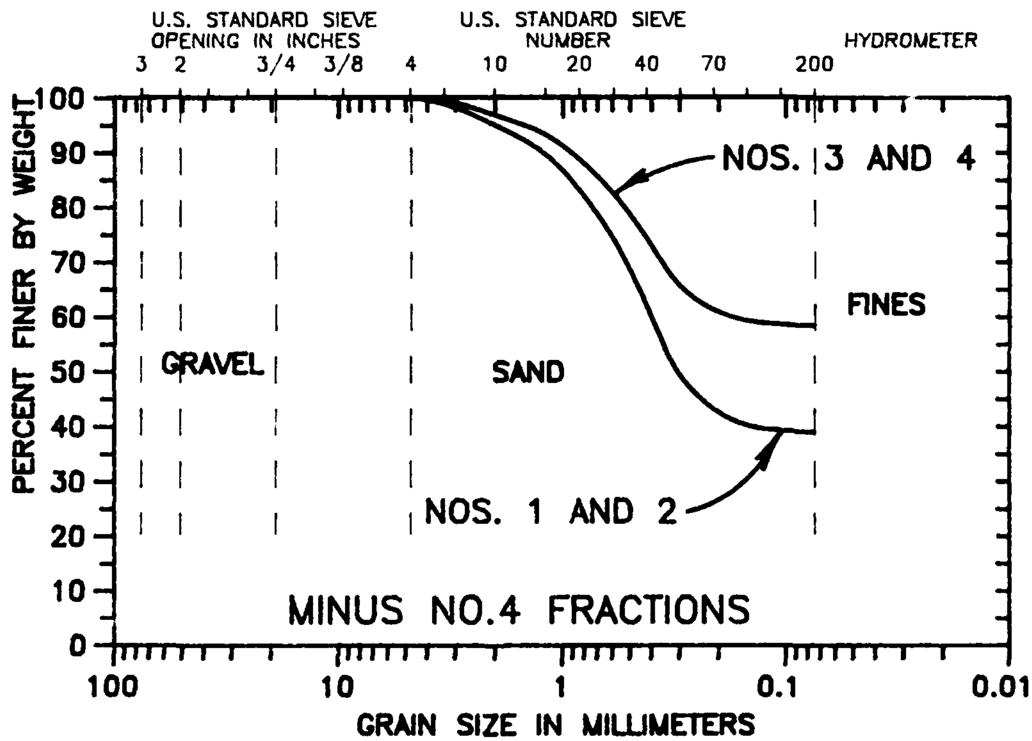


Figure 4. Example gradations, minus 3/4-in. and minus No. 4 fractions

$$I_c = \frac{R_c}{P_g G_m} \tag{6}$$

where

R_c = percent compaction of the finer fraction expressed as a decimal when the total material is at its maximum dry density γ_{tmax}

P_g = percent gravel (plus No. 4) in the total material expressed as a decimal

G_m = bulk specific gravity of the gravel, dimensionless

Example Calculations

19. Example calculations of I_c for minus 3-in. gradation No. 1 and its fractions containing gravel treated as total materials in their own right will be given below. Before presenting the calculations, it is necessary to point out that any values of maximum dry density and optimum water content are the result of the judgment of the individual fitting a compaction curve to the five compaction points ordinarily obtained. Because of variation which would be seen in curve fitting to the same data among several individuals, the value of maximum dry density is probably not really significant to even one decimal place. Furthermore, the values of gravel content and bulk specific gravity are not likely significant beyond two decimal places. However, for the purposes here, it will be presumed to calculate I_c to the third decimal place for reasons to be explained later.

Total material is minus 3-in. gradation No. 1
minus 3/4-in. fraction taken as the finer fraction

a. Calculating R_c. To obtain a value for R_c, the percent compaction of the finer fraction corresponding to the maximum dry density of the total material γ_{tmax} must be determined. To do this, use is made of Equation 1a and data from Table 1 as follows:

$$\gamma_f = \frac{f \gamma_t \gamma_w G_m}{\gamma_w G_m - c \gamma_t} \tag{1a}$$

From Table 1 it is seen that the maximum dry density for the minus 3-in. gradation No. 1 is 130.6 pcf. It is also seen that the percent oversize c or plus 3/4 in. is 20 percent (0.20) so that the percent finer fraction f or minus 3/4 in. is

80 percent (0.80). Note also from Table 1 that the bulk specific gravity G_m of the gravel is 2.68. Substitute the maximum dry density of 130.6 pcf for γ_t, c = 0.20, f = 0.80, and G_m = 2.68 into Equation 1a and calculate the dry density of the finer fraction γ_f as follows:

$$\gamma_f = \frac{(0.80)(130.6\ pcf)(62.4\ pcf)(2.68)}{(62.4\ pcf)(2.68) - (0.20)(130.6\ pcf)}$$

or

$$\gamma_f = 123.8\ pcf$$

So, when the minus 3-in. gradation No. 1 is at its maximum dry density of 130.6 pcf, the finer fraction (minus 3/4-in. fraction) within it is at a dry density of 123.8 pcf. Since the maximum dry density of the minus 3/4-in. fraction of gradation No. 1 is 123.5 pcf (see Table 1), its percent compaction R_c is:

$$R_c = \frac{\gamma_f}{\gamma_{fmax}} = \frac{123.8\ pcf}{123.5\ pcf} = 100.2\ percent$$

There is no cause for concern that the percent compaction of the finer fraction exceeds 100 percent when the total material is at its maximum dry density. It has been found for earth-rock mixtures containing clay fines and, say, less than about 30 to 35 percent gravel that this may be true. As gravel content increases above 30 to 35 percent, the percent compaction of the finer fraction begins to decline rapidly.

b. Calculating I_c. Now that a value of 1.002 (percentage expressed as a decimal) for R_c has been obtained, I_c can be calculated noting from Table 1 that the percent gravel P_g in the minus 3-in. gradation No. 1 is 28 percent (0.28) as follows:

$$I_c = \frac{R_c}{P_g G_m}$$

or

$$I_c = \frac{1.002}{(0.28)(2.68)} = 1.335$$

Minus 3-in. gradation No. 1, minus
No. 4 fraction taken as the finer fraction

a. Calculating R_c. Table 1 shows that the maximum dry density of minus 3-in. gradation No. 1 is 130.6 pcf; the percent oversize c with respect to the minus No. 4 fraction is 28 percent (same as the percent gravel in the minus 3-in. gradation); and the percent finer fraction f is, therefore, 72 percent. The dry density of the finer fraction γ_f when the minus 3-in. material is at its maximum dry density is from Equation 1a:

$$\gamma_f = \frac{(0.72)(130.6\ pcf)(62.4\ pcf)(2.68)}{(62.4\ pcf)(2.68) - (0.28)(130.6\ pcf)}$$

or

$$\gamma_f = 120.4\ pcf$$

From Table 1, the maximum dry density of the finer fraction (minus No. 4 fraction) is 118.6 pcf so that R_c becomes:

$$R_c = \frac{120.4\ pcf}{118.6\ pcf} = 101.5\ percent$$

b. Calculating I_c. With $R_c = 1.015$, $P_g = 0.28$, and $G_m = 2.68$, I_c calculates as:

$$I_c = \frac{1.015}{(0.28)(2.68)} = 1.353$$

Total material is minus 2-in. gradation No. 1
minus 3/4-in. fraction taken as finer fraction

a. Calculating R_c Table 1 shows that the maximum dry density of the minus 2-in. gradation No. 1 is 130.6 pcf, the percent oversize c with respect to the minus 3/4-in. (finer) fraction is 12.0 percent, and the percent finer fraction f is 88.0. The dry density of the finer fraction γ_f when the total material is at its maximum dry density using Equation 1a becomes:

$$\gamma_f = \frac{(.880)(130.6\ pcf)(62.4\ pcf)(2.68)}{(62.4\ pcf)(2.68) - (.120)(130.6\ pcf)}$$

or

$$\gamma_f = 126.8\ pcf$$

and, since from Table 1 the maximum dry density of the minus 3/4-in. fraction (finer fraction) is 123.5 pcf, R_c becomes

$$R_c = \frac{126.8\ pcf}{123.5\ pcf} = 102.7\ percent$$

b. Calculating I_c From Table 1, the percent gravel in the minus 2-in. gradation No. 1 is 20.9 percent (.209). I_c is then calculated as:

$$I_c = \frac{1.027}{(0.209)(2.68)} = 1.834$$

Total material is minus 2-in. gradation No. 1
minus No. 4 fraction taken as the finer fraction

a. Calculating R_c. Table 1 shows that the maximum dry density of the minus 2-in. gradation No. 1 is 130.6 pcf, the percent oversize c with respect to the minus No. 4 (finer) fraction is 20.9 percent, and the percent finer fraction f is 79.1. The dry density of the finer fraction when the total material is at its maximum dry density using Equation 1a becomes:

$$\gamma_f = \frac{(.791)(130.6\ pcf)(62.4\ pcf)(2.68)}{(62.4\ pcf)(2.68) - (.209)(130.6\ pcf)}$$

or

$$\gamma_f = 123.4\ pcf$$

Table 1 shows the maximum dry density of the minus No. 4 (finer) fraction of gradation No. 1 to be 118.6 pcf so that R_c becomes:

$$R_c = \frac{126.8\ pcf}{123.5\ pcf} = 102.7\ percent$$

b. Calculating I_c. Table 1 shows the percent gravel P_g in the minus 2-in. gradation No. 1 to be 20.9 percent. I_c is calculated as:

$$I_c = \frac{1.040}{(.209)(2.68)} = 1.857$$

Total material is minus 3/4-in. gradation No. 1 minus No. 4 fraction taken as the finer fraction

a. Calculating R_c. Table 1 shows that the maximum dry density of the minus 3/4-in. gradation No. 1 is 123.5 pcf, the percent oversize c with respect to the minus No. 4 (finer) fraction is 10 percent, and the percent finer fraction f is 90 percent. The dry density of the finer fraction when the total material is at its maximum dry density using Equation 1a becomes:

$$\gamma_f = \frac{(.90)(123.5\ pcf)(62.4\ pcf)(2.68)}{(62.4\ pcf)(2.68) - (.10)(123.5\ pcf)}$$

or

$$\gamma_f = 120.0\ pcf$$

Table 1 shows the maximum dry density of the minus No. 4 (finer) fraction of gradation No. 1 to be 118.6 pcf so that R_c becomes:

$$R_c = \frac{120.0\ pcf}{118.6\ pcf} = 101.2\ percent$$

b. Calculating I_c. Table 1 states the percent gravel in the minus 3/4-in. gradation No. 1 is 10.0 percent and I_c is then calculated as:

$$I_c = \frac{1.012}{(0.10)(2.68)} = 3.776$$

Values of I_c calculated for all the example gradations containing gravel of Figures 3 and 4 are summarized in Table 2 for the case where the minus 3/4-in. fraction is taken as the finer fraction and in Table 3 for the case where the minus No. 4 fraction is taken as the finer fraction.

Plotting I_c versus gravel content P_g

20. Figure 5 shows the values of the Density Interference Coefficient I_c based on the minus 3/4-in. fraction as the finer fraction plotted against gravel content P_g. Figure 6 shows I_c based on the minus No. 4 fraction as the finer fraction plotted against P_g. In both cases, it is seen that a smooth curve of I_c versus P_g can be excellently fitted to the trends. The shapes of the curves in the cartesian coordinates of Figures 5 and 6 suggest that they may become linear in log-log coordinates. Figure 7 shows I_c based on the minus 3/4-in. fraction as the finer fraction plotted versus gravel content P_g in log-log coordinates. Figure 8 shows I_c based on the minus No. 4 fraction as the finer fraction versus P_g in log-log coordinates. Figure 7 indicates that a straight line can indeed be fitted to I_c versus P_g over the entire range in gravel content (20.9 percent to 64 percent) when I_c is based on the minus 3/4-in. fraction as the finer fraction. However, Figure 8 reveals that, when I_c is based on the minus No. 4 fraction as the finer fraction, the trend is linear up to the gravel content of about 50 percent (minus 3-in. gradation No. 2, see Table 1) and appears to become curvilinear above that gravel content. The reason that I_c based on the minus 3/4-in. fraction versus P_g remains linear in log-log coordinates to higher gravel contents than I_c based on the minus No. 4 fraction is because the percent oversize is smaller when the finer fraction is taken as the minus 3/4-in. fraction. In other words, the percent oversize relative to the minus 3/4-in. fraction for the example gradations (see Table 1) never exceeds 40 percent while, relative to the minus No. 4 fraction, it reaches as much as 64 percent. If the trends seen for I_c versus P_g based on the minus No. 4 fraction in log-log coordinates (see Figure 8) held true for I_c versus P_g based on the minus 3/4-in. fraction, one would expect the log-log linear trend of Figure 7 to also become curvilinear as the percent oversize relative to the

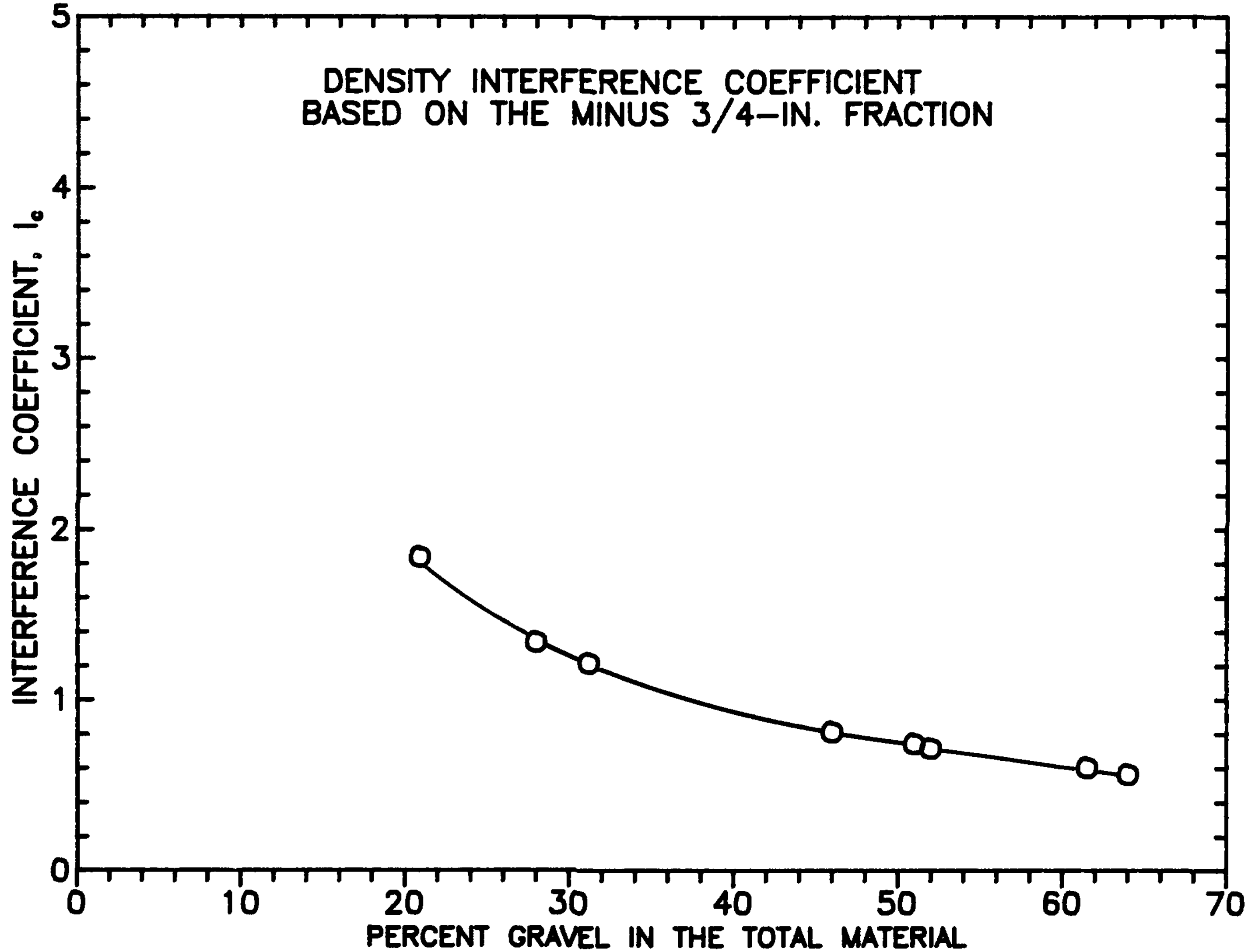


Figure 5. Example gradations, Density Interference Coefficients based on the minus 3/4-in. fraction versus gravel content plotted in cartesian coordinates

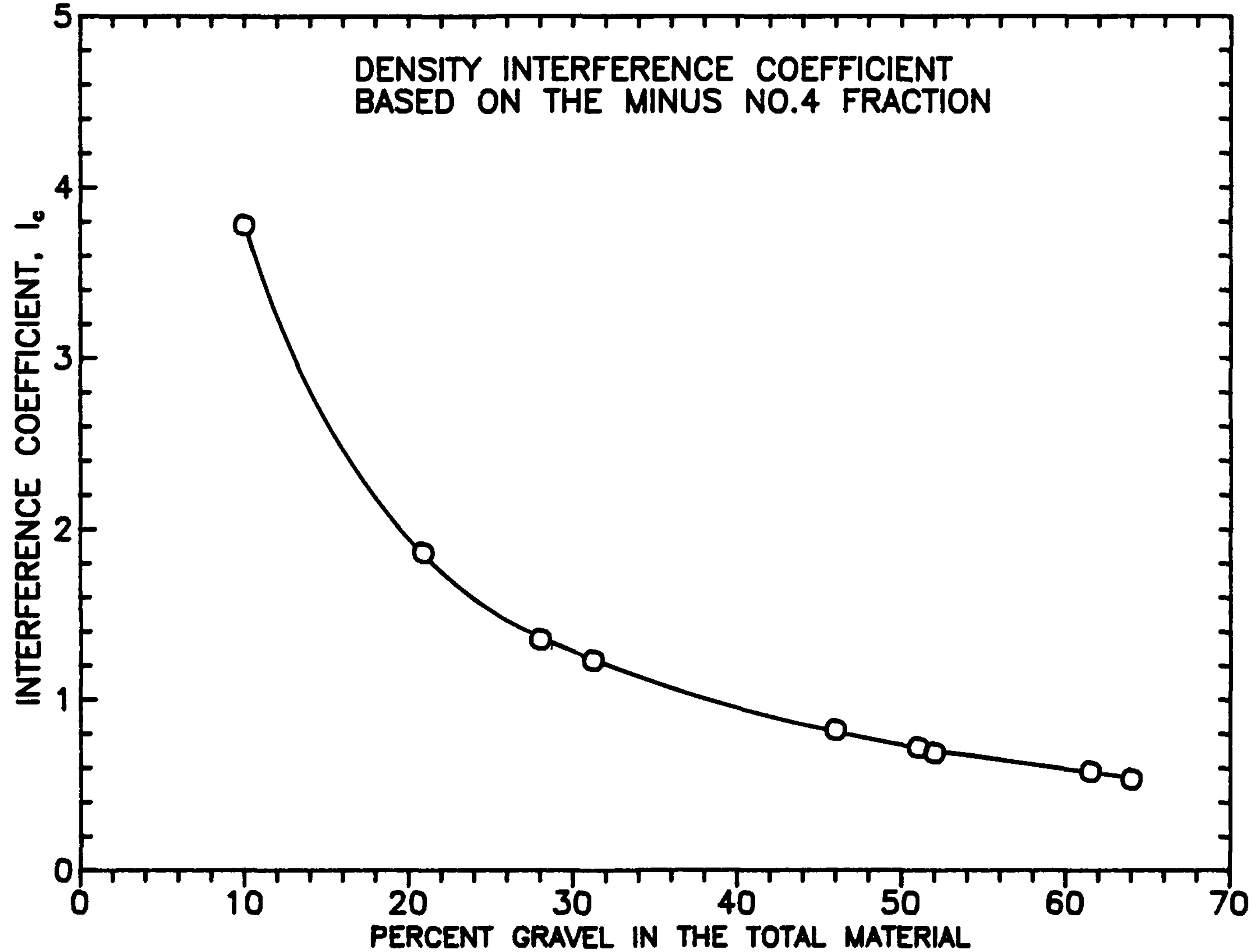


Figure 6. Example gradations, Density Interference Coefficients based on the minus No. 4 fractions versus gravel content plotted in cartesian coordinates

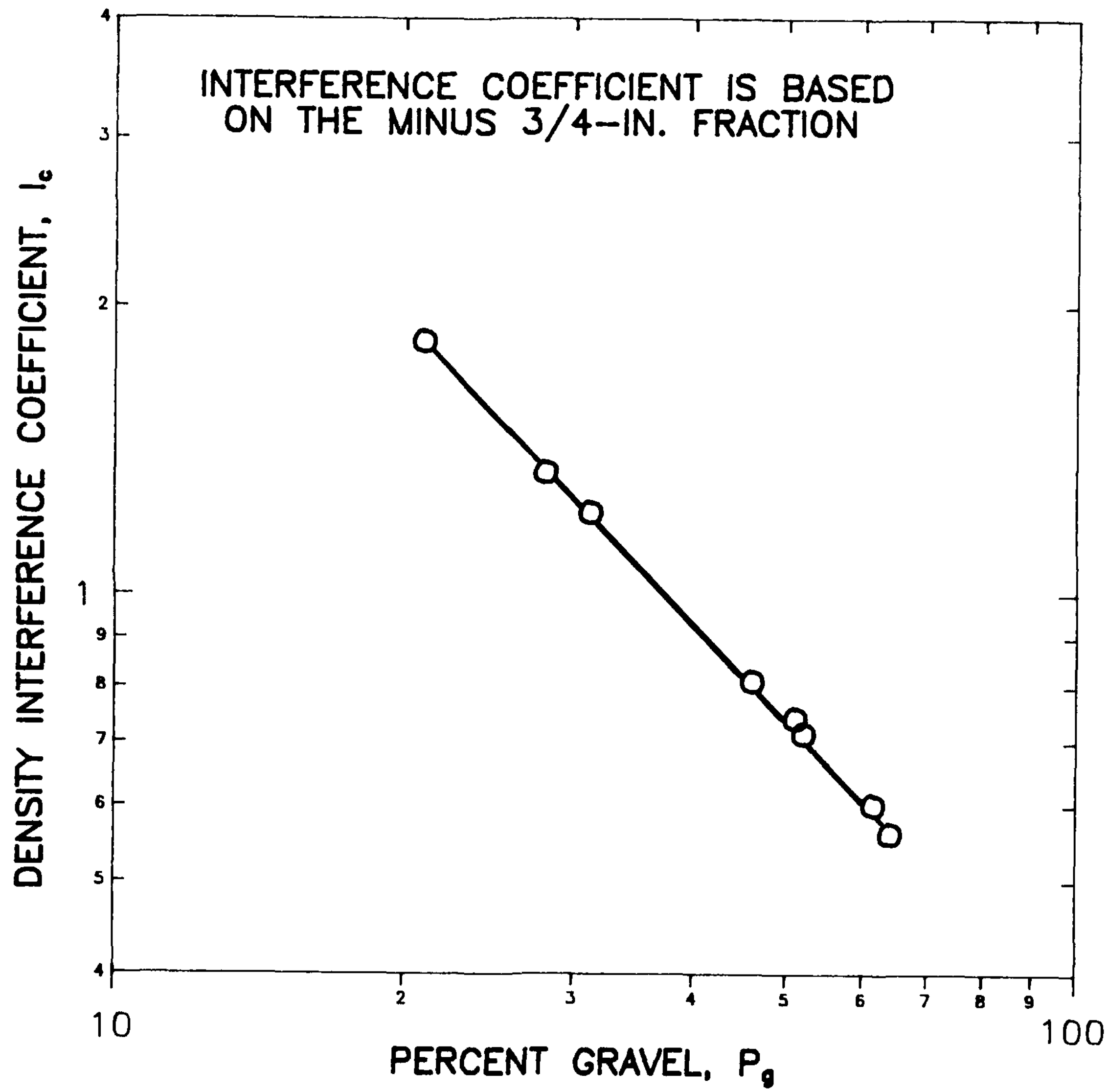


Figure 7. Example gradations, Density Interference Coefficients based on the minum 3/4-in. fractions versus gravel content plotted in log-log coordinates

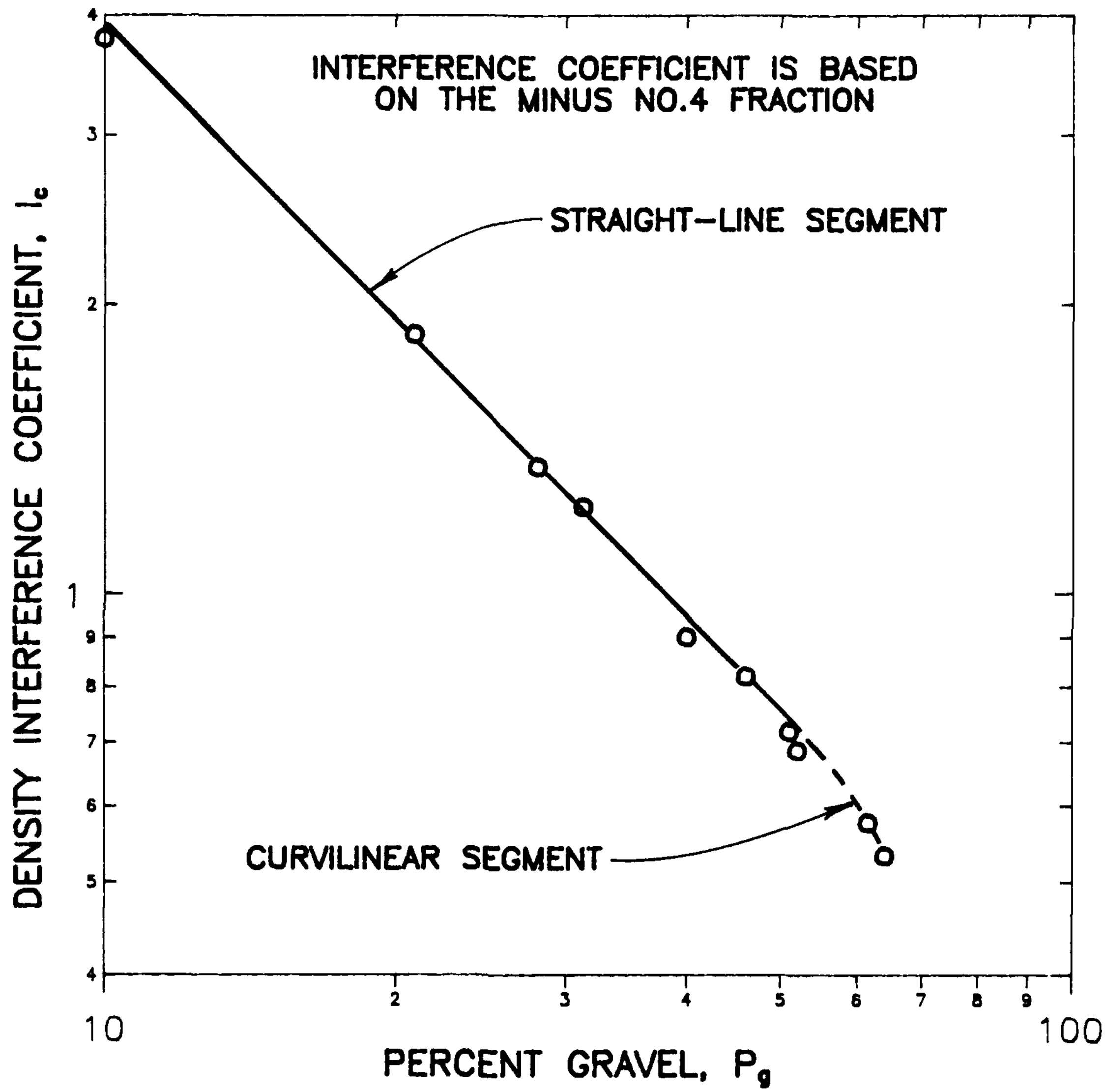


Figure 8. Example gradations, Density Interference Coefficients based on the minus No. 4 fractions versus gravel content plotted in log-log coordinates

minus 3/4-in. fraction began to also approach about 50 percent which for the example materials would correspond to a gravel content in excess of 70 percent.

Establishing I_c based on the minus No. 4 fraction versus P_g without large-scale compaction tests

21. It is important to point out that Figures 5 through 8 show that for the entire family of compaction curves shown in Figure 2 and corresponding to the gradations shown in Figures 3 and 4, all values of Density Interference Coefficient I_c based on a selected fraction calculated for the minus 3-in. total materials and any of their gravelly fractions will fall on a single curve versus gravel content P_g . If the minus No. 4 fraction is taken as the finer fraction, the linear portion of I_c versus P_g in log-log coordinates (Figure 8) can be established by compaction testing of only the minus 3/4-in. fractions and corresponding minus No. 4 fractions of the parent total gradations as long as the gravel contents of the minus 3/4-in. fractions span a large enough range to confidently establish a straight line through the data points. This should not be done by only employing the minus 3/4-in. fractions with the lowest and highest gravel contents from among the family of total materials encountered in the borrow area. Instead, several minus 3/4-in. fractions with intermediate gravel contents and their associated minus No. 4 fractions should also be tested so that the straight line can be best fitted within the small scatter of the total data. If the range in gravel content of the minus 3/4-in. fractions is not broad enough to confidently establish the log-log straight line, testing of minus 2-in. fractions after USACE (1970), Appendix VIA, must also be performed to obtain I_c values based on the minus No. 4 fraction corresponding to higher gravel contents of the minus 2-in. fractions. It must be remembered that the straight-lined relationship of I_c based on the minus No. 4 fraction versus gravel content P_g in log-log coordinates cannot be assumed valid above a gravel content of about 50 percent unless test results on the particular materials prove it so. However, Torrey and Donaghe (1991a and 1991b) showed that the approximate 50 percent gravel limit also applied to several other earth-rock mixtures reported in the literature. Part IV of this report will describe the use of I_c in determining the percent compaction of the total fill material. The procedure will require conversion of the linear log-log relationship between I_c and P_g back to

the curvilinear form of Figures 5 and 6 to permit an easier determination of values of I_c given the gravel content P_g in the fill density sample.

22. If any of the full-scaled gradations from the borrow source contain more than about 50 percent gravel, two alternative procedures may be used to establish the trend in I_c versus P_g above that gravel content. If I_c is based on the minus 3/4-in. fraction, the log-log relationship between I_c and gravel content remains linear up to a gravel content nearing 65 percent. However, if I_c is based on the minus No. 4 fraction, the relationship is no longer linear in log-log coordinates above 50 percent gravel content. Torrey and Donaghe (1991a) examined the compaction data published by several different investigators which included a wide range in earth-rock gradations. They discovered that the slopes of the curves of I_c versus P_g based on the minus No. 4 fraction as the finer fraction tended to become linear in cartesian coordinates (such as Figure 6) above a gravel content of 50 percent. Figure 9 shows that the linear slopes in this range were very similar and exhibited an average value of 0.0132. Take note that Figure 9 is not plotted to equal scales on the X and Y axes so that the slopes of the lines are not directly indicated. Part IV of this report describing the new compaction control or quality assurance procedure will provide instructions as to how to extend the curve of I_c versus P_g to gravel contents above 50 percent using this average slope if I_c is based on the minus No. 4 fraction.

Optimum Water Content Factor F_{opt} Versus Gravel Content P_g

Calculating F_{opt}

23. Just as for the case of I_c , Optimum Water Content Factors F_{opt} can be based either on the minus 3/4-in. or minus No. 4 fraction as the finer fraction. Example calculations for gradation No. 1 and its fractions of Figures 3 and 4 will be given below. For convenience, Equation 9 defining the Optimum Water Content Factor F_{opt} is repeated as follows:

$$F_{opt} = \frac{W_{fopt}}{P_g W_{topt}} \tag{9}$$

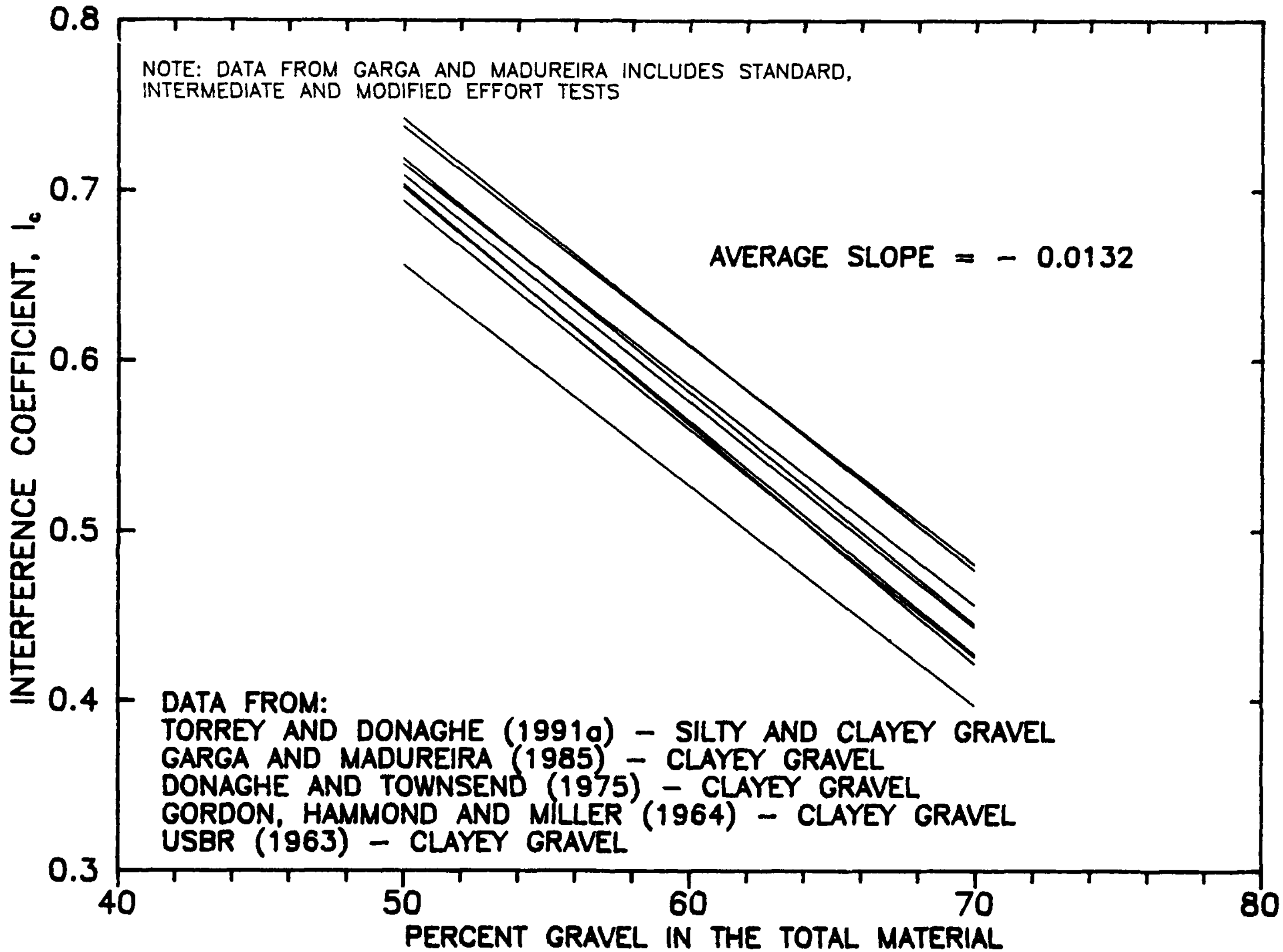


Figure 9. Slope of the I_c versus P_g curve in cartesian coordinates for gravel contents in excess of 50 percent

24. <u>F_{opt} based on the minus 3/4-in. fraction</u>. The following values of F_{opt} are calculated treating the minus 3-in. gradation No. 1 and its minus 2-in. fraction of Figure 3 each as if they were total materials.

a. <u>Minus 3-in. gradation No. 1 taken as the total material</u>. From Table 1, the optimum water content of the minus 3-in. gradation No. 1 W_{topt} is 8.4 percent, the percent gravel P_g is 28 percent, and the optimum water content of the minus 3/4-in. fraction W_{fopt} is 10.7 percent. The Optimum Water Content Factor based on the minus 3/4-in. fraction then becomes:

$$F_{opt} = \frac{W_{fopt}}{P_g W_{topt}} = \frac{10.7}{(0.28)(8.4)} = 4.549$$

b. <u>Minus 2-in. gradation No. 1 taken as the total material</u>. From Table 1, the optimum water content of the minus 2-in. gradation No. 1 W_{topt} is 8.4 percent, the percent gravel P_g is 20.9 percent, and the optimum water content of the minus 3/4-in. fraction W_{fopt} is 10.7 percent. The Optimum Water Content factor based on the minus 3/4-in. fraction then becomes:

$$F_{opt} = \frac{10.7}{(0.209)(8.4)} = 6.095$$

25. <u>F_{opt} based on the minus No. 4 fraction</u>. The following values of F_{opt} are calculated treating the minus 3-in., minus 2-in., and minus 3/4-in. gradations No. 1 each as if it were a total material.

a. <u>Minus 3-in. gradation No. 1 taken as the total material</u>. From Table 1, the optimum water content of the minus 3-in. gradation No. 1 W_{topt} is 8.4 percent, the percent gravel P_g is 28 percent, and the optimum water content of the minus No. 4 fraction W_{fopt} is 12.9 percent. F_{opt} is then calculated as:

$$F_{opt} = \frac{W_{fopt}}{P_g W_{topt}} = \frac{12.9}{(0.28)(8.4)} = 5.485$$

b. <u>Minus 2-in. gradation No. 1 taken as the total material</u>. From Table 1, the optimum water content of the minus 2-in. gradation No. 1 is 8.4 percent, the percent gravel is 20.9 percent, and the optimum water content of the minus No. 4 fraction is 12.9 percent. F_{opt} is then calculated as:

$$F_{opt} = \frac{12.9}{(0.209)(8.4)} = 7.348$$

c. <u>Minus 3/4-in. gradation No. 1 taken as the total material</u>. From Table 1, the optimum water content of the minus 3/4-in. gradation No. 1 is 10.7 percent, the percent gravel is 10 percent, and the optimum water content of the minus No. 4 gradation No. 1 is 12.9 percent. F_{opt} becomes:

$$F_{opt} = \frac{12.9}{(0.10)(10.7)} = 12.056$$

26. Table 4 summarizes the values of Optimum Water Content Factor F_{opt} based on the minus 3/4-in. fraction as the finer fraction calculated for the minus 3-in. and minus 2-in. gravelly gradations shown in Figures 3 and 4 and listed in Table 1. Table 5 summarizes the values of F_{opt} based on the minus No. 4 fraction as calculated for the minus 3-in., minus 2-in., and minus 3/4-in. gradations shown in Figures 3 and 4 and listed in Table 1.

<u>Plotting F_{opt} versus gravel content</u>

27. Figure 10 shows the Optimum Water Content Factors F_{opt} based on both the minus 3/4-in. and minus No. 4 fractions as the finer fraction plotted versus gravel content P_g . Just as for the case of Density Interference Coefficients versus gravel content (see Figures 5 and 7), smooth curves can be drawn to nicely fit the trends of F_{opt} versus gravel content. Figure 11 shows that the trends appear to be linear when the data are plotted in log-log coordinates. More scatter is observed in the data of Figures 10 and 11 than was evident for the case of the Density Interference Coefficient I_c versus gravel content (Figures 5 through 8). This results from the greater impact on the value of the Optimum Water Content Factor resulting from the judgment in determining optimum water content from standard five-point compaction data. In other words, a tenth of one percentage point difference in judging the value of optimum water content is more significant relative to values falling in the 7 to 15 percent range (see Table 1) than is a tenth of 1 pcf relative to values of maximum dry density falling in the 110 to 138-pcf range for the materials as seen in Table 1. The data scatter, therefore, reflects the "precision" of the compaction test in general. The subject of compaction test precision will be briefly spoken to in Part IV of this report.

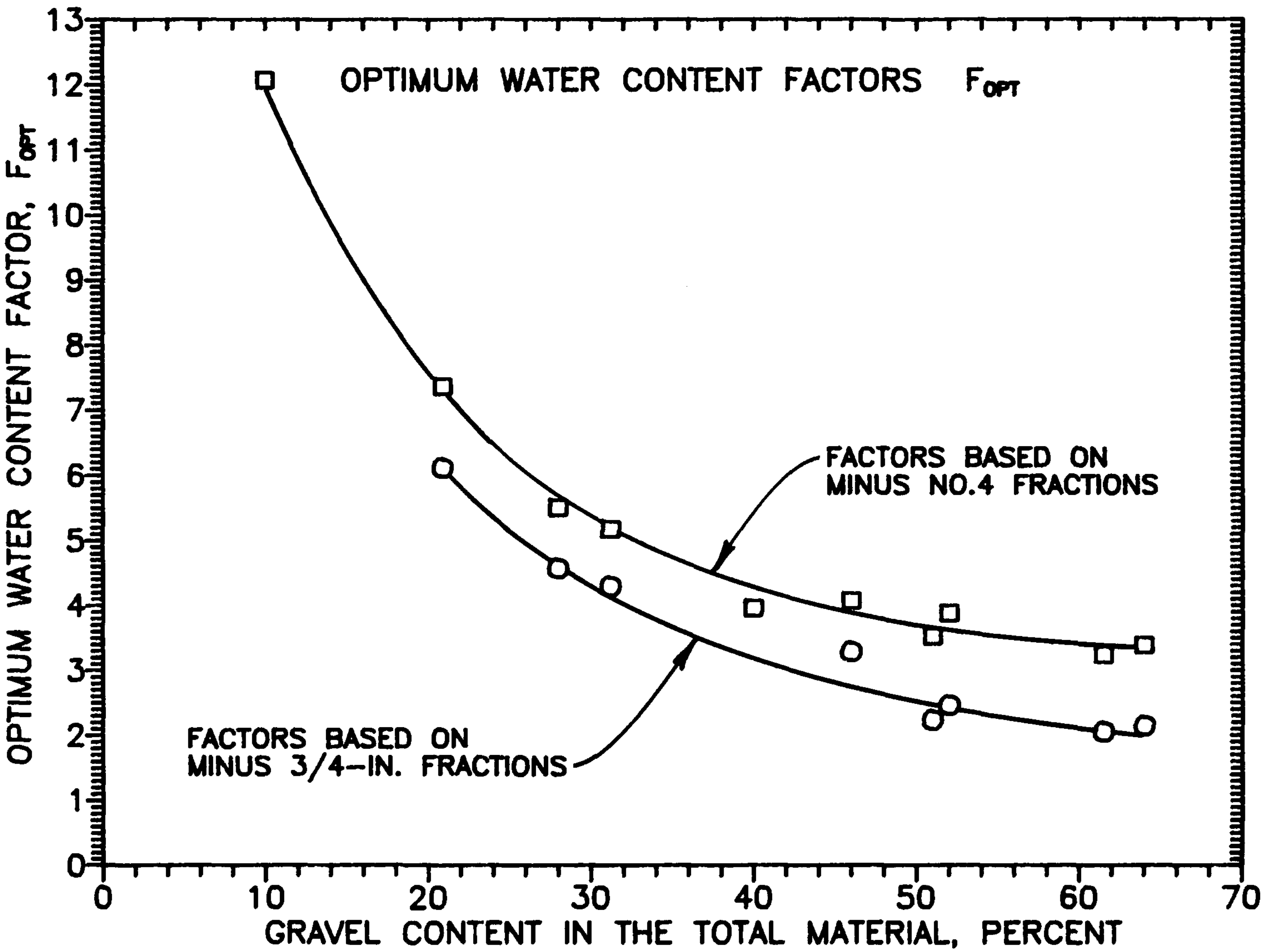


Figure 10. Example gradations, Optimum Water Content Factors based on the minus 3/4-in. and minus No. 4 fractions plotted in cartesian coordinates

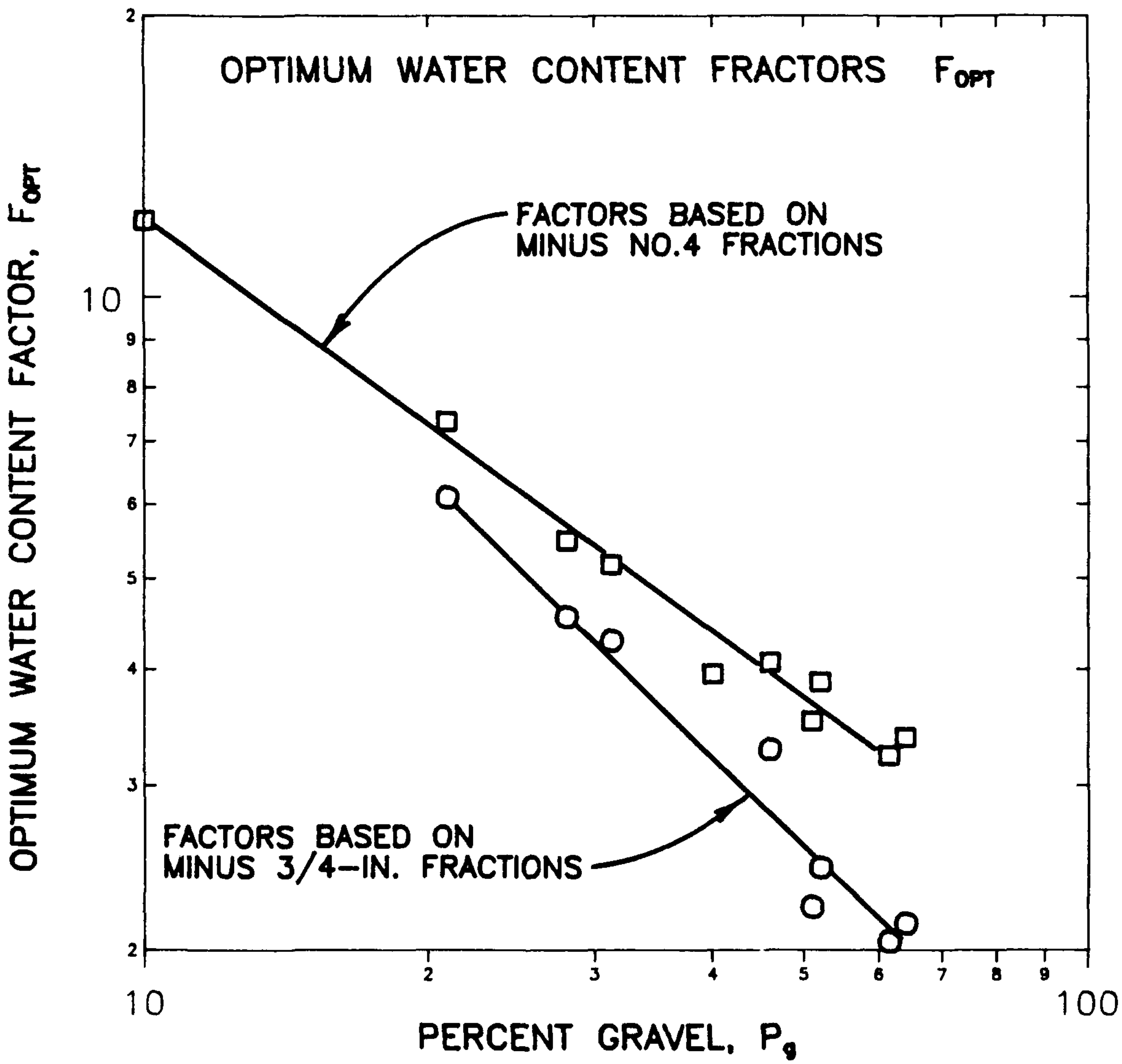


Figure 11. Example gradations, Optimum Water Content Factors based on the minum 3/4-in. and minus No. 4 fractions plotted in log-log coordinates

Establishing F_{opt} based on the minus No. 4 fraction versus P_g without large-scale compaction tests

28. It is seen in Figure 11 that the Optimum Water Content Factors based on the minus No. 4 fraction and calculated treating the minus 3/4-in. gradations as if they were total materials all fall on the same straight line as those calculated for the minus 3-in. and minus 2-in. gradations. Just as was the case for the Density Interference Coefficient, this offers the possibility to establish the straight line in log-log coordinates for an entire family of related gradations by performing compaction tests on only the minus 3/4-in. and minus No. 4 fractions. Again, in order that the straight line be established with confidence, it is necessary that the range in gravel content of the minus 3/4-in. fractions be sufficiently broad and several minus 3/4-in. fractions with intermediate gravel contents (and the associated minus No. 4 fractions) be included in the testing along with those exhibiting the minimum and maximum gravel contents. Should the gravel content range of the minus 3/4-in. fractions not be sufficient to establish the log-log straight line confidently, values of F_{opt} based on the minus No. 4 fraction corresponding to higher gravel contents must be obtained by testing minus 2-in. fractions using the procedure of USACE (1970), Appendix VIA.

29. There is no clear deviation from linearity of F_{opt} versus P_g evident in Figure 11 at gravel contents as high as 64 percent which was the maximum for the example minus 3-in. gradation No. 4 of Table 1. However, it should not be presumed in general practice to extend the straight line obtained by the shortcut method based on the minus 3/4-in. and minus No. 4 fractions described above beyond a gravel content of 50 percent without some large-scaled testing of at least minus 2-in. fractions (USACE 1970), Appendix VIA, to lend credence to a linear trend at higher gravel contents.

PART IV: THE COMPACTION CONTROL OR QUALITY ASSURANCE PROCEDURE

General

30. The methods to be described below presume that the compaction specifications refer to the compacted state of the total material such that quality control or quality assurance fill density test results are compared directly with values of maximum dry density and optimum water contents for the total material to obtain values of fill percent compaction and deviation of fill water content from optimum water content. So, the following paragraphs provide instructions concerning the techniques of calculating the maximum dry density and optimum water content of the total material represented by the compaction control or quality assurance fill density sample using the relationships among the Density Interference Coefficient I_c, the Optimum Water Content Factor F_{opt}, and the percent gravel P_g in the fill density sample. The procedures are very simple and are previewed in summary as follows:

a. Establish the curves of I_c and F_{opt} versus gravel content P_g during the preconstruction phase of the project employing samples of the materials to be placed in the embankment obtained from the planned borrow sources.

b. Also during the preconstruction phase of the project, decide whether to use the minus 3/4-in. fraction or the minus No. 4 fraction of the fill density sample as the finer fraction. Then, develop the necessary families of five-point compaction curves for the selected finer fraction employing samples from the planned borrow sources. These families of curves will be used to obtain values of maximum dry density γ_{fmax} and optimum water content W_{fopt} of the finer fraction during construction control using the one- or two-point compaction method described in USACE (1977), Appendix B. Of course, other methods as described in USACE (1977), Appendix B, may be used to obtain the required finer fraction maximum dry density and optimum water content. The one- or two-point method is cited here because it has been the most popular choice within the USACE.

c. Determine the bulk specific gravity G_m of the coarser fraction.

d. During fill operations, determine the fill dry density γ_t, the fill water content W_t, the gravel content P_g of the fill density sample, the percent oversized fraction c of the fill density sample, and the percent finer fraction f of the fill density sample.

e. With the percent gravel P_g of the fill density sample, enter the curves of I_c and F_{opt} versus gravel content P_g and

pick off values for I_c and F_{opt} or calculate the values using the equations for the curves.

f. Perform a one- or two-point compaction test on the finer fraction representing the fill density sample and determine the maximum dry density γ_{fmax} and optimum water content W_{fopt} for that finer fraction using the appropriate family of finer fraction compaction curves established in b. above.

g. Substitute the values of I_c, P_g, c, f, G_m, and γ_{fmax} into Equation 8 previously given as follows:

$$\gamma_{tmax} = \frac{I_c P_g \gamma_{fmax} \gamma_w G_m}{f\gamma_w + c I_c P_g \gamma_{fmax}} \tag{8}$$

and calculate the value of the maximum dry density corresponding to the fill density sample γ_{tmax}.

h. Calculate the fill percent compaction by dividing the value of the fill dry density γ_t determined from the fill density test by the value of maximum dry density for the fill sample γ_{tmax} calculated in step g. above.

i. Substitute the values of W_{fopt}, F_{opt} and P_g into the following rearranged version of Equation 9

$$W_{topt} = \frac{W_{fopt}}{P_g F_{opt}}$$

and calculate the value of the optimum water content for the fill density sample W_{topt}.

j. Compare the value of the water content of the fill density sample W_t with its optimum water content W_{topt} calculated in step i. above and calculate the deviation of fill water content from optimum water content.

31. It is appropriate to issue a warning relative to the method chosen to obtain values of the maximum dry density and optimum water content of the finer fraction as described in b. above. Obviously, the ultimate quality of the compaction control or quality assurance method to be described below (or any other method) is directly dependent on the precision of the values of maximum dry density and optimum water content ascribed to the fill density sample. If the family or families of five-point compaction curves for the finer fractions of the range of borrow materials are thoroughly developed to clearly identify "lines of optimums" (see Figure 2), the estimates of maximum dry density and optimum water content obtained from one- or two-point compaction tests during construction should be adequately precise. That is to say

that the values should fall within the range of values which would be obtained if a series of five-point repetitive tests were performed on each single material sample and compaction curves fitted independently to each five-point data set. A single technician performing a series of five-point compaction tests on the same material and fitting a compaction curve to each data set without cross-reference or memory of any other results obtained will cite a range in maximum dry density and optimum water content for that material. This is what is meant by the fundamental precision of the compaction test itself. The US Bureau of Reclamation Rapid Compaction Control Method which is now an ASTM (1991c) standard is actually a three-point compaction method on the minus No. 4 fraction coupled with a graphical procedure for fitting a parabolic compaction curve through the data points. That method is also satisfactory. Correlations among maximum dry density, optimum water content, and the Atterberg Limits, as described in USACE (1977), Appendix B, are not recommended because of the significant scatter typically seen in plots of maximum dry density or optimum water content versus Liquid or Plastic Limit. The visual compaction control method described in USACE (1977), Appendix B, should never be used for any embankment where engineering properties of the compacted soil are critical to its satisfactory and safe performance. A thorough discussion of precision of the compaction test and problems associated with the various control methods are given by Torrey and Donaghe (1991b).

Selecting the Finer Fraction

32. It has been previously shown that both the Density Interference Coefficient I_c and the Optimum Water Content Factor F_{opt} can be calculated by taking either the minus 3/4-in. or minus No. 4 fraction as the finer fraction. The summary procedures given above indicate that selection of the minus No. 4 fraction as the finer fraction offers several advantages over use of the minus 3/4-in. fraction. If the minus No. 4 fraction is designated as the finer fraction, less material is required for compaction tests and the smaller, more convenient 4-in. diam mold may be used. Furthermore, if the minus No. 4 fraction is designated, the percent oversize c becomes equivalent to the percent gravel P_g. If the minus 3/4-in. fraction is designated as the finer fraction, two sieving operations on material taken from the

location of each fill density sample would be required to determine P_g (the plus No. 4 fraction) and the percent oversize c (the plus 3/4-in. fraction).

33. In cases where the gravel content exceeds 50 percent, use of the minus No. 4 fraction as the finer fraction would entail developing the I_c versus P_g curve in two pieces as has already been suggested and will be described later. The two-piece approach to establishing the curve for I_c based on the minus No. 4 fraction versus P_g for materials containing more than 50 percent gravel to be given later herein will be an approximate approach in order to maintain the avoidance of large-scale compaction testing of the total materials. Therefore, that procedure will be deliberately prescribed to yield accurate to conservative calculated values of the maximum dry density of the fill density sample. Conservative calculated values of maximum dry density corresponding to the fill density sample are those which, if they cannot be certified as accurate, will be slightly higher than actual values rather than lower than actual values. This practice will ensure that calculated values of percent compaction will be correct to slightly lower than actual values in order to avoid overly optimistic assessment of the compacted state of the fill.

34. There is a circumstance which might make it preferable to designate the minus 3/4-in. fraction as the finer fraction. In the event that gravel contents of the fill material are mostly greater than 50 percent, it may be preferable to take advantage of the linearity of the log-log version of the curve of I_c versus gravel content P_g up to percent oversize c (plus 3/4-in. fraction) approaching 50 percent.

35. The instructions and discussions to follow will be predicated on the following:

a. The minus No. 4 fraction is taken as the finer fraction.

b. The linear portion of the relationship between I_c and P_g plotted in log-log coordinates has been established for the fill material using minus 3/4-in. fractions and minus No. 4 fractions, i.e. the shortcut method previously described.

c. The linear relationship in log-log coordinates between F_{opt} and P_g has been established for the fill material using minus 3/4-in. fractions and minus No. 4 fractions, i.e., the shortcut method previously described.

d. The values of fill dry density γ_t and fill water content W_t have been determined by a fill density test.

e. The values of maximum dry density γ_{fmax} and optimum water content W_{fopt} corresponding to the minus No. 4 (finer) fraction

of the fill density sample have been determined by, say, a one- or two-point compaction test applied to an appropriate family of five-point compaction tests performed on the minus No. 4 fractions of the range of borrow materials.

Determining the Maximum Dry Density Associated With the Fill Density Sample

I_c versus P_g: gravel content less than 50 percent by weight

36. If the gravel content of the fill density sample P_g is less than 50 percent by weight, the relationship between I_c and the gravel content P_g can be assumed to be linear in log-log coordinates as in Figure 8 up to the gravel content of 50 percent. However, it is difficult to enter a log-log plot with a value of P_g and accurately pick off the corresponding value of I_c . Therefore, it is best to convert the straight line obtained in log-log coordinates back to cartesian coordinates. The data and fitted straight line previously shown in Figure 8 are replotted in Figure 12 except that data relative to gravel contents above 50 percent are omitted since another method to establish this range in the curve of I_c versus P_g in cartesian coordinates will be treated later. The general procedure to obtain the curve in cartesian coordinates is as follows:

a. The equation of the straight line in log-log coordinates of Figure 12 is of the form:

$$LOG\ I_c = a_0 + a_1\ LOG\ P_g \tag{10}$$

where

a_0 = a constant to be determined

a_1 = the slope of the line which in this case is negative

b. The slope a_1 of the line is determined by physically measuring with any convenient scale the vertical distance A-C and the horizontal distance A-B in Figure 12 and then obtaining the ratio of A-C to A-B, i.e., A-C/A-B. Note that this is not a logarithmic ratio. From Figure 12, this ratio becomes -1.025 because the slope of the line is negative (downward to the right).

c. The value of the constant a_0 must be determined by substituting the value for the slope a_1 and the I_c and P_g coordinates for any known point on the line into Equation 10 above

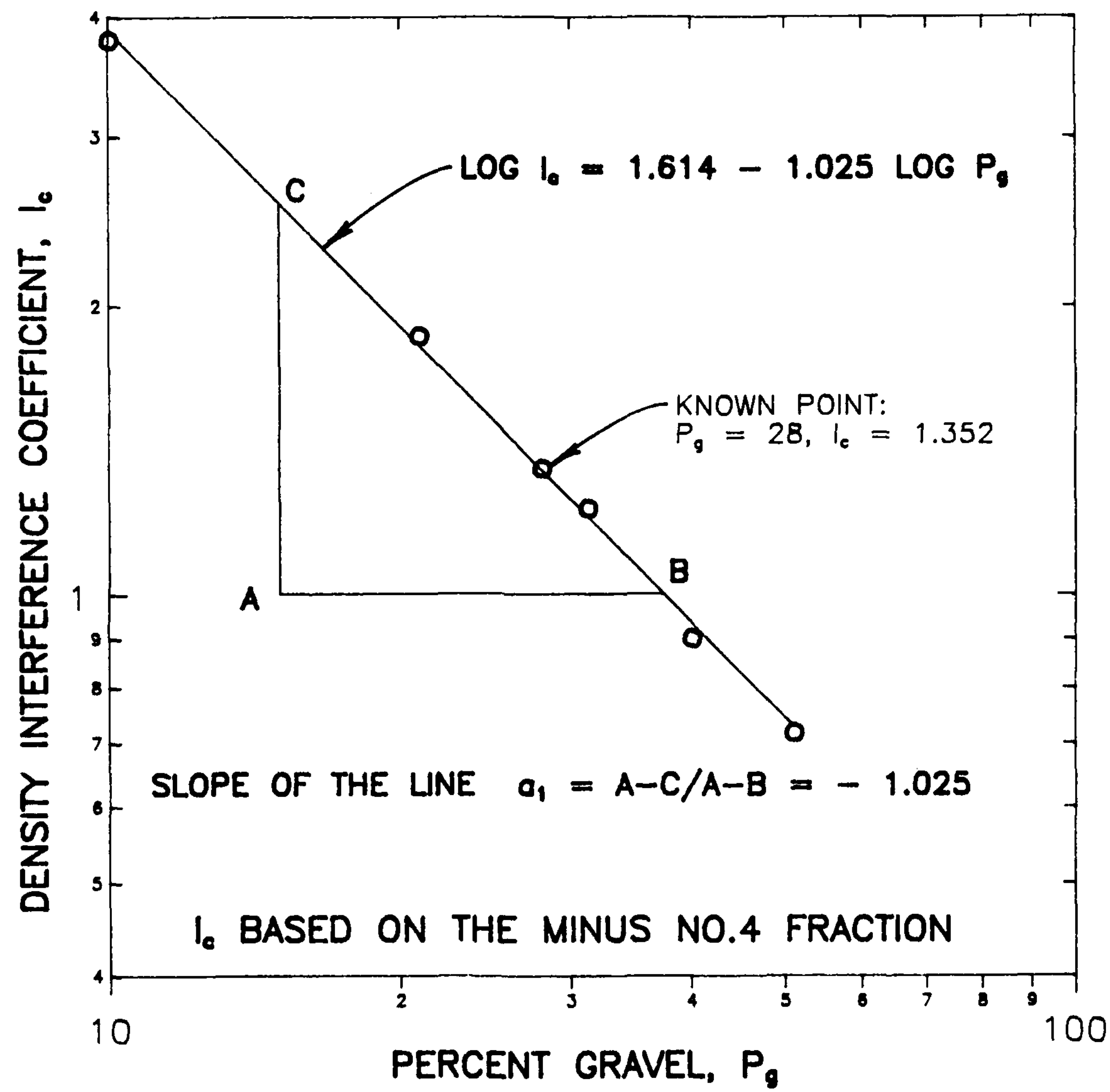


Figure 12. Example gradations with P_g less than 50 percent, I_c based on the minus No. 4 fraction, equation of the straight line of best fit in log-log coordinates

and solving for the value of a_0 . It so happens in the fitting of the straight line to the data of Figure 12 that the data point at $P_g = 28$ percent falls directly on the line. From Table 3, the minus 3-in. gradation No. 1 contains 28 percent gravel and exhibited a value of I_c of 1.352. Therefore, a_0 is calculated as follows:

$$LOG\ 1.352 = a_0 + (-1.025)\ LOG\ 28.000$$

or

$$a_0 = LOG\ 1.352 + 1.025\ LOG\ 28.000$$

$$a_0 = 0.131 + (1.025)(1.447) = 1.614$$

And, the equation of the line to be plotted in cartesian coordinates becomes:

$$LOG\ I_c = 1.614 + (-1.025)\ LOG\ P_g$$

or

$$LOG\ I_c = 1.614 - 1.025\ LOG\ P_g \tag{11}$$

d. Now, a range in values of P_g can be substituted into Equation 11 to calculate the corresponding values for I_c as follows:

P_g	Calculated I_c
10.000	3.776
15.000	2.525
20.000	1.898
30.000	1.270
40.000	0.954
45.000	0.849
50.000	0.746

e. The data of d. above are shown plotted in cartesian coordinates in Figure 13 with a smooth curve drawn through the points.

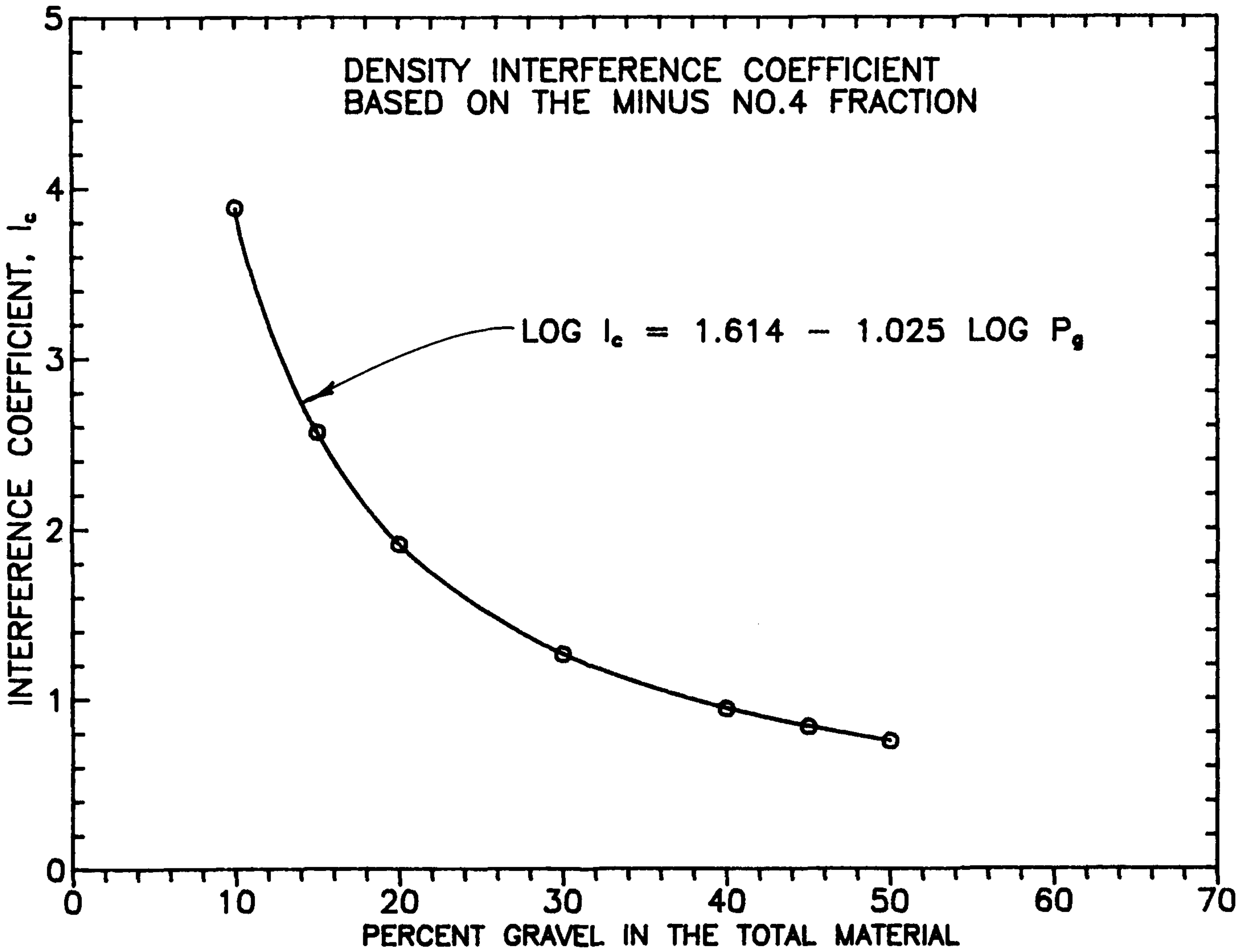


Figure 13. Example gradations with P_g less than 50 percent, I_C based on the minus No. 4 fraction, log-log straight line of best fit plotted in cartesian coordinates

37. *It is the more desirable practice to use the equation for the curve such as Equation 11 above to calculate values of* I_c *directly from the gravel content* P_g *determined for the fill density sample. It is important to note that all calculations above have been made to the nearest third decimal place. It is also acceptable to obtain the value of* I_c *graphically from the plot of* I_c *versus* P_g *such as that shown in Figure 13. The graph should be plotted to a scale such that values of* I_c *can be picked off the curve to the nearest third decimal place. This requires an over-sized piece of graph paper and is not practical in this report. The value of the maximum dry density of the fill density sample to be calculated from the value of* I_c *is sensitive to relatively small changes in the value of* I_c *. So, while the third decimal place is not mathematically significant, the provision for calculating values of* I_c *from the equation or reading from the curve to three decimal places is a means of preventing sloppiness in using the values.*

I_c versus P_g :
gravel content ranges in
excess of 50 percent by weight

38. If I_c is based on the minus No. 4 fraction and gravel content in the fill material ranges to values which exceed 50 percent, the curve of I_c versus P_g in cartesian coordinates of Figure 13 must be extended above that value by an approximate procedure. It was pointed out earlier that Torrey and Donaghe (1991a and 1991b) discovered for a significant range in earth-rock mixture data that the slope of the I_c versus P_g curve becomes linear in cartesian coordinates above a gravel content of about 50 percent. Those linear slopes varied little among the materials examined and averaged -0.0132 (see Figure 9). The curve of Figure 13 can be extended beyond 50 percent gravel by affixing a straight line through the data point at 50 percent gravel on a slope of -0.0132 as shown in Figure 14 and described as follows.

a. A straight line in cartesian coordinates of I_c versus P_g would have the following equation:

$$I_c = b + s_1 P_g \tag{12}$$

where

b = the value of I_c where the straight line would intersect the y-axis, i.e., at $P_g = 0$. This value will have to be calculated.

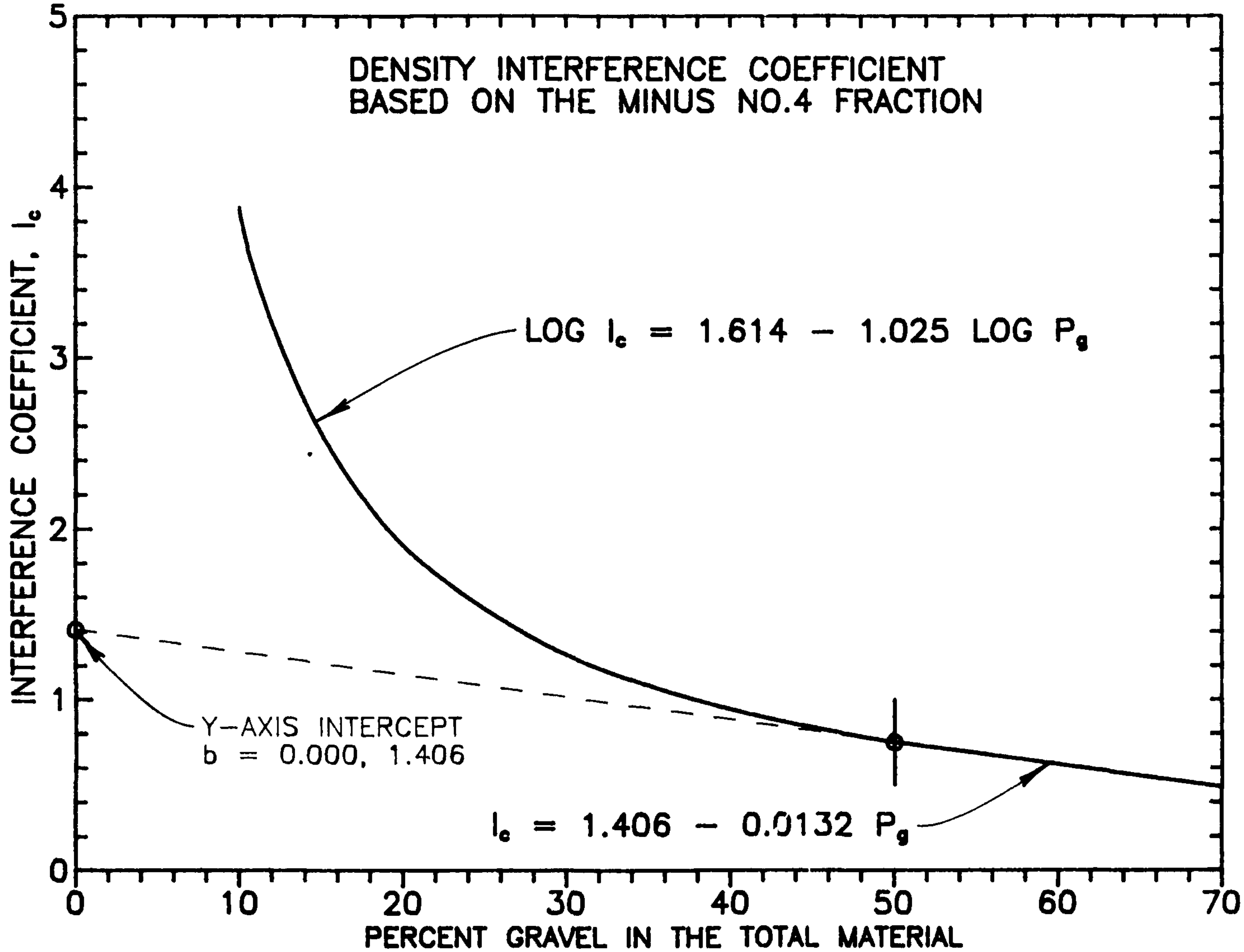


Figure 14. Example gradations, I_c based on the minus No. 4 fraction versus P_g, extending the curve to gravel contents above 50 percent

s_1 = the slope of the line which is specified as -0.0132

b. Since the line is to pass through the known point at P_g equal to 50 percent and I_c = 0.746 (see paragraph 35 d.), these two coordinates can be substituted into Equation 12 along with the value of the slope to calculate the y-axis intercept b as follows:

$$0.746 = b + (-0.0132)(50)$$

$$b = 1.406$$

So, the equation of the straight line to extend the curve of Figure 14 from the point of 50 percent gravel to higher gravel contents becomes:

$$I_c = 1.406 + (-0.0132)\ P_g$$

$$I_c = 1.406 - 0.0132\ P_g \qquad (13)$$

c. The easy way to place the line on Figure 14 is to plot the point of the y-axis intercept b (P_g = 0.0, I_c = b = 1.406) and then draw the line through that point and the point at P_g = 50 percent and I_c = 0.746 as shown in Figure 14.

39. *It must not be presumed to extend the curve of Figure 14 beyond 70 percent gravel since this was the highest gravel content providing data for Figure 9 from the literature. The compaction traits of earth-rock mixtures containing higher gravel contents are beyond the scope of any research known to the author. After the gravel content reaches a level where the gravel particles come into contact within the mix, the finer fraction may no longer fill the voids between the gravel particles. In this case, the basic weight-volume equation for calculating the dry density of the finer fraction or the total material is no longer valid. Again, it is preferable to calculate* I_c *for gravel contents in excess of 50 percent by entering the gravel content of the fill density sample* P_g *into the equation for the straight line (such as Equation 13 above) rather than picking the value from a plot of the line.*

Calculating the maximum dry density γ_{tmax} associated with the fill density sample

40. Once the curve of I_c versus P_g such as that of Figure 14 has been established, it may be employed to obtain the appropriate value of I_c corresponding to the gravel content in the fill density sample. It is also necessary to have the value of the maximum dry density of the finer fraction γ_{fmax} which has been determined by the one- or two-point compaction method using material from the fill density sample location. For the purposes of illustration, example gradations of Table 1 will have to be employed since the maximum dry density of their minus No. 4 fractions (finer fractions) are known. First, the value of I_c will be calculated using Equation 12 for minus 2-in. gradation No. 2 since it has a gravel content less than 50 percent, i.e., 31.2 percent. Then another value of I_c will be calculated using Equation 13 for minus 3-in. gradation No. 4 since it has a gravel content more than 50 percent, i.e., 64 percent. After these two values are obtained, corresponding values of maximum dry density to be associated with the respective minus 2-in. and minus 3-in. gradations will be calculated. Of course, in the actual control or quality assurance case, the calculated values of maximum dry density of the total material γ_{tmax} would correspond to the fill density sample.

a. I_c for minus 2-in. gradation No. 2. Table 1 shows that $P_g = 31.2$ so that Equation 11 yields for I_c :

$$LOG\ I_c = 1.614 - 1.025\ LOG\ 31.2$$

$$LOG\ I_c = 1.614 - (1.025)(1.494)$$

$$LOG\ I_c = 0.083$$

$$I_c = 10^{0.083} = 1.210$$

b. I_c for minus 3-in. gradation No. 4. Table 1 shows that $P_g = 64$ so that Equation 13 yields:

$$I_c = 1.406 - 0.0132\ P_g$$

$$I_c = 0.561$$

c. Calculating the maximum dry density for the fill density sample. The bulk specific gravity G_m for the example soils is 2.68 and the maximum dry density of the finer fraction (minus No. 4) is 118.6 pcf (Table 1, minus No. 4 gradation Nos. 1 and 2). Also, since I_c is based on the minus No. 4 fraction, the percent oversized fraction c and the percent gravel P_g are the same value. Equation 8 is used to calculate the maximum dry density associated with the total material of the fill density sample as follows:

Minus 2-in. gradation No. 2:
$P_g = 0.312$, $I_c = 1.210$, $c = 0.312$, $f = 0.688$, $\gamma_{fmax} = 118.6$ pcf

$$\gamma_{tmax} = \frac{I_c P_g \gamma_{fmax} \gamma_w G_m}{f\gamma_w + cI_c P_g \gamma_{fmax}} \tag{8}$$

substituting

$$\gamma_{tmax} = \frac{(0.312)(1.210)(118.6)(62.4)(2.68)}{(0.688)(62.4) + (.312)(.312)(1.210)(118.6)}$$

$$\gamma_{tmax} = 131.6\ pcf$$

Note from Table 1 that the test value for this gradation is 133.1 pcf. The 1.5-pcf difference between the calculated value above and the test value is well within the level of precision of the compaction test itself. In other words, if a series of five-point compaction tests were performed on this material by a single individual, the range in values of maximum dry density he would obtain by independently fitting each data set with a compaction curve would exceed 1.5 pcf.

Minus 3-in. gradation No. 4:
$P_g = 0.64$, $I_c = 0.561$, $c = 0.64$, $f = 0.36$, $\gamma_{fmax} = 110.0$ pcf

$$\gamma_{tmax} = \frac{(0.64)(0.561)(110.0)(62.4)(2.68)}{(0.36)(62.4) + (0.64)(0.64)(0.561)(110.0)}$$

$$\gamma_{tmax} = 138.3 \ pcf$$

Note from Table 1 that the test value of maximum dry density obtained for this gradation was 134.9 pcf. The calculated value of 138.3 pcf is conservative as intended since the value of fill percent compaction based on this number will be lower than that actually achieved in the fill (about two percent lower in this case).

41. Now that calculations of the maximum dry density of the total material have been made using I_c based on the minus No. 4 fraction, the calculations for the same two gradations using I_c based on the minus 3/4-in. fraction will be shown. In this case, the linear fit in log-log coordinates to I_c versus gravel content P_g from Figure 7 is adequate throughout the range in gravel content. To make the calculations, an equation must be obtained for the log-log straight line of Figure 7 as previously described. That equation is found to be as follows:

$$LOG\ I_c = 1.648 - 1.049\ LOG\ P_g \tag{14}$$

a. I_c for minus 2-in. gradation No. 2.. Table 1 shows that P_g = 31.2 percent so that Equation 14 yields:

$$LOG\ I_c = 1.648 - 1.049\ LOG\ (31.2)$$

$$LOG\ I_c = 1.648 - (1.049)(1.494)$$

$$LOG\ I_c = 0.081$$

$$I_c = 10^{0.081} = 1.204$$

b. I_c for minus 3-in. gradation No. 4. Table 1 shows that P_g = 64.0 percent so that Equation 14 yields:

$$LOG\ I_c = 1.648 - 1.049\ LOG\ (64)$$

$$LOG\ I_c = 1.648 - (1.049)(1.806)$$

$$LOG\ I_c = -0.246$$

$$I_c = 10^{-0.246} = 0.567$$

c. Calculating the maximum dry density for the fill density sample. The bulk specific gravity G_m for the example soils is 2.68 and the maximum dry density of the finer fraction (minus 3/4-in.) is 123.5 pcf (Table 1, Minus 3/4-in. gradation Nos. 1 and 2). Since I_c is based on the minus 3/4-in. fraction, the percent oversize c and the percent gravel P_g are not the same quantity. Equation 8 is used to calculate the maximum dry density associated with the total material of the fill density sample as follows:

Minus 2-in. gradation No. 2:
From Table 1, it is seen that the percent oversize c with respect to the minus 3/4-in. fraction is 23.6 percent while the percent gravel P_g is 31.2 percent. Therefore, the percent finer fraction f is (100 - c) or 76.4. Also from Table 1, the maximum dry density of the minus 3/4-in. fraction is 123.5 pcf (minus 3/4-in. fractions 1 and 2).

$$\gamma_{tmax} = \frac{I_c P_g \gamma_{fmax} \gamma_w G_m}{f\gamma_w + c I_c P_g \gamma_{fmax}} \qquad (8)$$

substituting

$$\gamma_{tmax} = \frac{(1.204)(0.312)(123.5)(62.4)(2.68)}{(0.764)(62.4) + (0.236)(1.204)(0.312)(123.5)}$$

$$\gamma_{tmax} = 132.3 \ pcf$$

Note from Table 1 that the value of the maximum dry density obtained from the large-scale compaction test on this gradation was 133.1 pcf. The difference of 0.8 pcf between the calculated value and this test value is well within the precision of the compaction test itself.

Minus 3-in. gradation No. 4:
$P_g = 0.64$, $I_c = 0.567$, $c = 0.40$, $f = 0.60$, $\gamma_{fmax} = 124.3$ pcf

$$\gamma_{tmax} = \frac{(0.567)(0.64)(124.3)(62.4)(2.68)}{(0.60)(62.4) + (0.40)(0.567)(0.64)(124.3)}$$

$$\gamma_{tmax} = 135.9 \ pcf$$

Note that Table 1 shows that the value of the maximum dry density obtained from the large-scale compaction test on this gradation was 134.9 pcf. The difference of 1.0 pcf between the calculated value and this test value is well within the precision of the compaction test itself. This example illustrates that basing I_c on the minus 3/4-in. fraction when the borrow materials regularly exhibit gravel contents in excess of 50 percent is superior to use of the minus No. 4 fraction. The trade off in using I_c based on the minus 3/4-in. fraction is that two sieving operations are required on material taken from the location of the fill density sample because both the percent gravel P_g (plus No. 4 fraction) and the percent oversize c (plus 3/4-in. fraction) must be determined.

42. The value of the maximum dry density γ_{tmax} calculated as shown above can then be compared with the dry density γ_t obtained from the fill density test to calculate the percent compaction of the fill.

Determining the Optimum Water Content Associated With the Fill Density Sample

F_{opt} versus P_g

43. The procedures for determining the optimum water content for the fill density sample are similar to those shown for obtaining a value for the maximum dry density. The reader is reminded of the assumptions given in paragraph 34 for the examples to follow, i.e. :

a. The minus No. 4 fraction is taken as the finer fraction.

b. The linear relationship in log-log coordinates between F_{opt} and P_g has been established for the fill material using minus 3/4-in. fractions and minus No. 4 fractions, i.e., the shortcut method previously described.

c. The values of fill dry density γ_t and fill water content W_t have been determined by a fill density test.

d. The values of maximum dry density γ_{fmax} and optimum water content W_{fopt} corresponding to the minus No. 4 (finer) fraction of the fill density sample have been determined by, say, a one- or two-point compaction test applied to an appropriate family of five-point compaction tests performed on the minus No. 4 fractions of the range of borrow materials.

44. The linear log-log relationship between F_{opt} and P_g for the minus No. 4 fraction of Figure 11 is replotted in Figure 15. The first step is to determine the equation for the line using the procedures previously illustrated in Figure 12. In the case of F_{opt} versus P_g of Figure 15, the fitted straight line does not pass through one of the calculated data points so that a data point lying on the line is picked off for use in determining the equation of the line. This has been done by selecting a value of F_{opt} of 6.000 and then determining the corresponding value of P_g of 26.1 percent. The slope of the line determined by ratioing the length A-B to the length A-C using any convenient scale is -0.730. The equation of the line is then:

$$LOG\ F_{opt} = a_1 + (-.730)\ LOG\ P_g$$

from which

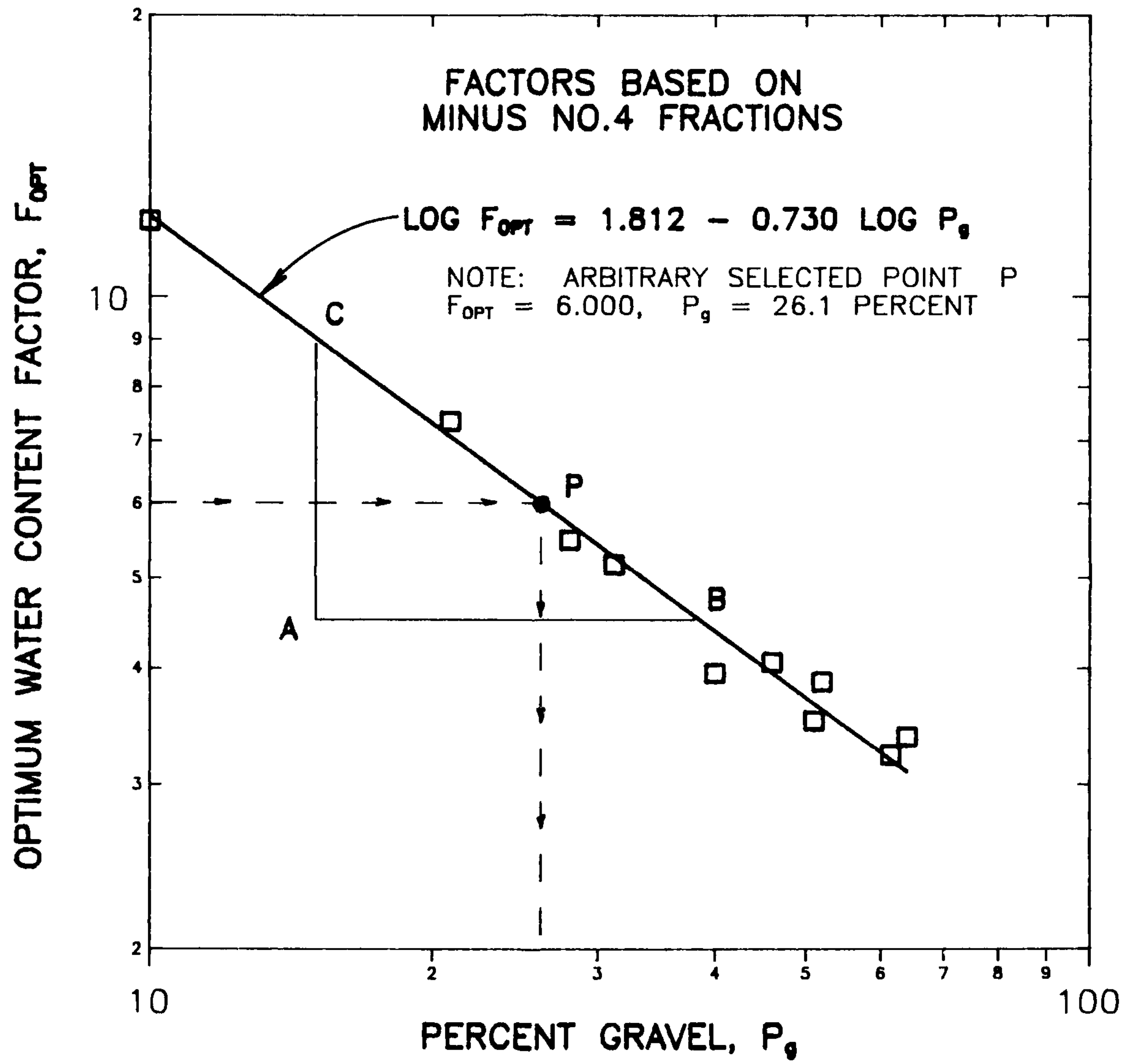


Figure 15. Example gradations, F_{OPT} based on the minus No. 4 fraction, equation of the straight line of best fit in log-log coordinates

$$a_1 = LOG\ F_{opt} + 0.730\ LOG\ P_g$$

substituting the known point $F_{opt} = 0.600$ and $P_g = 26.1$ yields

$$a_1 = LOG\ 6.000 + 0.730\ LOG\ 26.1$$

or

$$a_1 = 0.778 + (0.730)(1.417) = 1.812$$

The Equation of the straight line of Figure 15 is then:

$$LOG\ F_{opt} = 1.812 - 0.730\ LOG\ P_g \tag{15}$$

Having the Equation 15, values of P_g can be substituted and corresponding values of F_{opt} calculated as follows:

P_g	Calculated F_{opt}
10.000	12.078
15.000	8.984
20.000	7.282
30.000	5.416
40.000	4.390
50.000	3.730
64.000	3.115

These values are shown plotted in Figure 16 with a smooth curve fitted. As was the case for the Density Interference Coefficient I_c, if it is decided to pick values of F_{opt} for field control purposes from a curve such as Figure 16 using the gravel content of the fill density sample, the curve should be plotted to a large enough scale such that F_{opt} can be read to the nearest third decimal place. The preferable approach is to use the equation obtained for the curve such as Equation 15 to calculate F_{opt} to three decimal places by substituting the value of gravel content of the fill density sample.

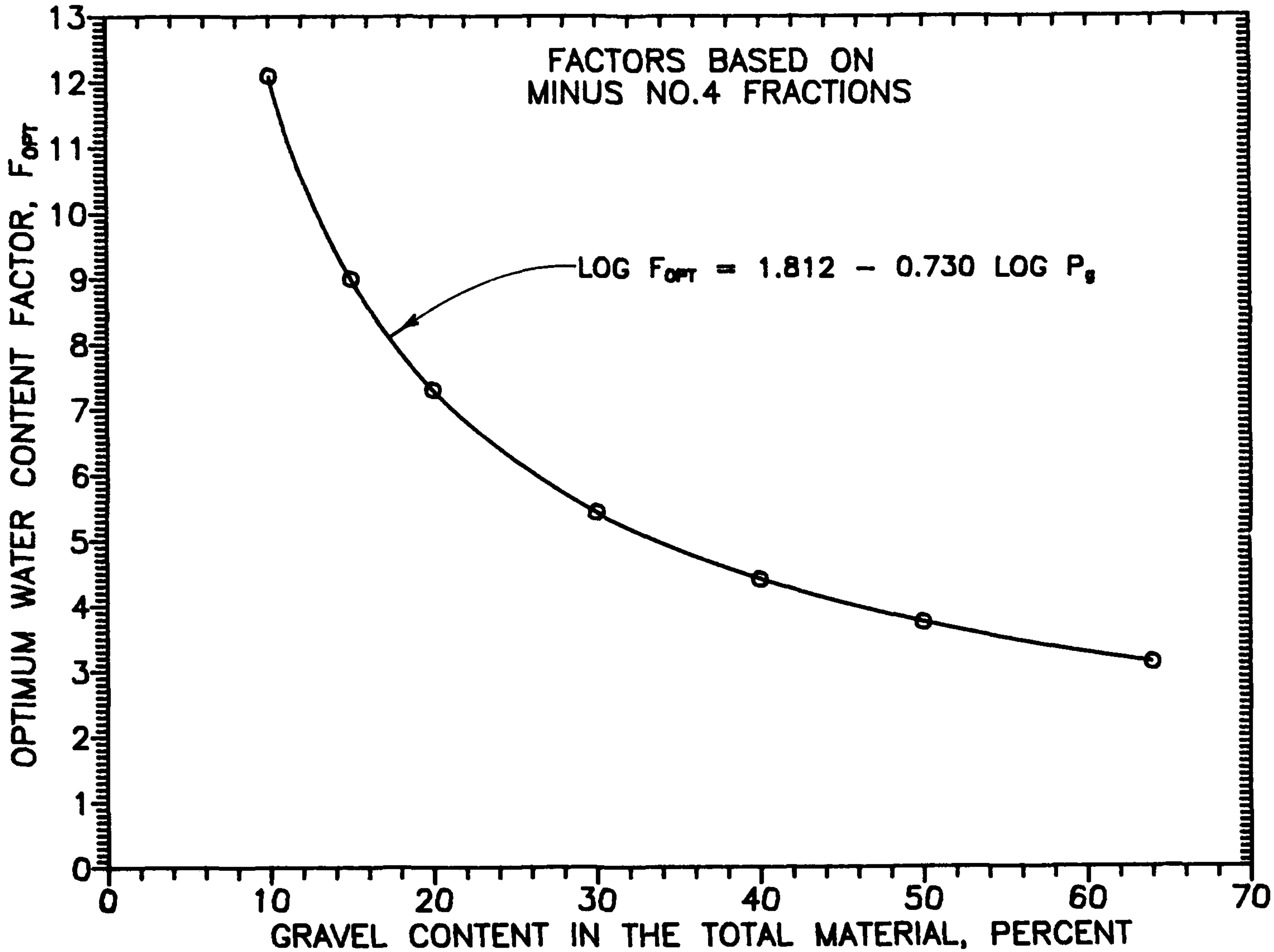


Figure 16. Example gradations, F_{OPT} based on the minus No. 4 fraction, log-log straight line of best fit plotted in cartesian coordinates

Calculating the optimum
water content W_{topt}
associated with the fill density sample

45. The following example calculations are made for minus 2-in. gradation No. 2 since the optimum water content of the minus No. 4 fraction is known from Table 1. In the fill control case, the optimum water content of the minus No. 4 fraction of the fill density sample would have been determined by some method such as the one- or two- point compaction method.

a. F_{opt} for minus 2-in. gradation No. 2. Table 1 shows that $P_g = 31.2$ percent and F_{opt} is calculated from Equation 15 as follows:

$$LOG\ F_{opt} = 1.812 - 0.730\ LOG\ P_g \qquad (15)$$

$$LOG\ F_{opt} = 1.812 - 0.730\ LOG\ 31.2$$

$$LOG\ F_{opt} = 1.812 - (0.730)(1.494) = 0.721$$

$$F_{opt} = 10^{0.721} = 5.260$$

b. Calculating the optimum water content for the fill density sample. Table 1 shows that the optimum water content W_{fopt} of the minus No. 4 fraction of minus 2-in. gradation No. 2 is 12.9 percent (minus No. 4 gradation Nos. 1 and 2). The defining equation for the optimum water content factor F_{opt} is Equation 9 as follows:

$$F_{opt} = \frac{W_{fopt}}{P_g W_{topt}} \qquad (9)$$

$$W_{topt} = \frac{W_{fopt}}{P_g F_{opt}}$$

substituting $P_g = 0.312$, $F_{opt} = 5.260$, and $W_{fopt} = 12.9$

$$W_{topt} = \frac{12.9}{(0.312)(5.260)} = 7.9 \text{ percent}$$

Note from Table 1 that the test value for this gradation was 8.0 percent optimum water content. Remember that P_g is substituted as a decimal and the optimum water content of the finer fraction is substituted as either a percentage or a decimal and the calculated value for the total material W_{topt} will be in the same units.

46. After a value of optimum water content for the fill density sample has been obtained after the fashion shown above, the fill water content of that fill density sample can be compared with it to determine the deviation of fill water content from optimum water content.

Summary Comments

47. The author believes that the new compaction control or quality assurance method described herein offers the ability to determine the maximum dry density and optimum water content of a gravelly soil from corresponding values obtained on the minus 3/4-in or minus No. 4 fraction to a precision which is as good as if large-scale compaction tests were performed on the total material. Of course, the precision of the new approach is directly dependent upon that of the means of identifying the maximum dry density and optimum water content of the fraction. For this reason, considerable care should be exercised in selecting, developing, and using a short-cut method such as the one- or two-point compaction procedure to determine the compaction parameters for the fraction.

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Table 1

Summary of Pertinent Data for Minus 3-in. Total Materials and Their Fractions

Gradation No.	Percent Oversize: Plus 3/4 in. 6-in. mold	Percent Oversize: Plus No. 4 4-in. mold	Percent Gravel	Maximum Dry Density pcf	Optimum Water Content percent
Minus 3-in. total materials					
1	20	28	28	130.6	8.4
2	40	46	46	137.8	7.1
3	20	52	52	130.3	7.3
4	40	64	64	134.9	6.8
Minus 2-in. fractions					
1	12	20.9	20.9	130.6	8.4
2	23.6	31.2	31.2	133.1	8.0
3	18.4	51	51	131.7	8.2
4	35.8	61.5	61.5	135.8	7.4
Minus 3/4-in. fractions					
1 and 2	0	10	10	123.5	10.7
3 and 4	0	40	40	124.3	9.3
Minus no. 4 fractions					
1 and 2	0	0	0	118.6	12.9
3 and 4	0	0	0	110.0	14.7

Bulk specific gravity of the gravel G_m is 2.68

NOTE: Maximum dry densities and optimum water contents of the minus 3-in. and minus 2-in. gradations were determined using the compaction test procedure developed for a mechanical compactor by Torrey and Donaghe (1991a). The minus 3-in. material was compacted in an 18-in. diam mold and the minus 2-in. material in a 12-in. diam mold.

Table 2

Density Interference Coefficients Based on the Minus 3/4-in. Fraction

Gradation	Percent Gravel P_g	c	f	γ_f* -3/4 in. pcf	R_c	G_m	I_c
No. 1, minus 3 in.	28	0.20	0.80	123.8	1.002	2.68	1.336
No. 1, minus 2 in.	20.9	0.12	0.88	126.8	1.027	2.68	1.834
No. 2, minus 3 in.	46	0.40	0.60	123.3	0.998	2.68	0.809
No. 2, minus 2 in.	31.2	0.236	0.764	125.2	1.014	2.68	1.213
No. 3, minus 3 in.	52	0.20	0.80	123.5	0.994	2.68	0.713
No. 3, minus 2 in.	51	0.184	0.816	125.7	1.011	2.68	0.740
No. 4, minus 3 in.	64	0.40	0.60	119.5	0.961	2.68	0.560
No. 4, minus 2 in.	61.5	0.358	0.642	122.9	0.989	2.68	0.600

* γ_f of the minus 3/4-in. fraction determined from Equation 1a using the maximum dry unit weight of the cited minus 3-in. or minus 2-in. gradations which are given in Table 1.

Table 3

Density Interference Coefficients Based on the Minus No. 4 Fraction

Gradation	Percent Gravel P_g	c	f	γ_f* -3/4 in. pcf	R_c	G_m	I_c
No. 1, minus 3 in.	28	0.28	0.72	120.3	1.014	2.68	1.352
No. 1, minus 2 in.	20.9	0.209	0.791	123.5	1.041	2.68	1.859
No. 1, minus 3/4 in.	10	0.10	0.90	120.0	1.012	2.68	3.776
No. 2, minus 3 in.	46	0.46	0.54	119.8	1.010	2.68	0.819
No. 2, minus 2 in.	31.2	0.312	0.688	121.8	1.027	2.68	1.228
No. 2, minus 3/4 in.	10	0.10	0.90	120.0	1.012	2.68	3.776
No. 3, minus 3 in.	52	0.52	0.48	105.1	0.955	2.68	0.685
No. 3, minus 2 in.	51	0.51	0.49	107.8	0.980	2.68	0.717
No. 3, minus 3/4 in.	40	0.40	0.60	106.1	0.965	2.68	0.900
No. 4, minus 3 in.	64	0.64	0.36	100.4	0.913	2.68	0.532
No. 4, minus 2 in.	61.5	0.615	0.385	104.4	0.949	2.68	0.576
No. 4, minus 3/4 in.	40	0.40	0.60	106.1	0.965	2.68	0.900

* γ_f of the minus No. 4 fraction determined from Equation 1a using the maximum dry unit weight of the cited minus 3-in., minus 2-in. or minus 3/4-in. gradations which are given in Table 1.

Table 4

Optimum Water Content Factors F_{opt} Based on the Minus 3/4-in. Fraction

Gradation	Percent Gravel P_g	Optimum Water Contents: Total Material W_{topt} percent	Optimum Water Contents: Minus 3/4-in. Fraction W_{fopt} percent	Optimum Water Content Factor F_{opt}
No. 1, minus 3 in.	28	8.4	10.7	4.549
No. 1, minus 2 in.	20.9	8.4	10.7	6.095
No. 2, minus 3 in.	46	7.1	10.7	3.276
No. 2, minus 2 in.	31.2	8.0	10.7	4.287
No. 3, minus 3 in.	52	7.3	9.3	2.450
No. 3, minus 2 in.	51	8.2	9.3	2.224
No. 4, minus 3 in.	64	6.8	9.3	2.137
No. 4, minus 2 in.	61.5	7.4	9.3	2.044

Table 5

Optimum Water Content Factors F_{opt} Based on the Minus No. 4 Fraction

Gradation	Percent Gravel P_g	Optimum Water Contents: Total Material W_{topt} percent	Optimum Water Contents: Minus No. 4 Fraction W_{fopt} percent	Optimum Water Content Factor F_{opt}
No. 1, minus 3 in.	28	8.4	12.9	5.485
No. 1, minus 2 in.	20.9	8.4	12.9	7.348
No. 1, minus 3/4 in.	10	10.7	12.9	12.056
No. 2, minus 3 in.	46	6.9	12.9	4.064
No. 2, minus 2 in.	31.2	8.0	12.9	5.168
No. 2, minus 3/4 in.	10	10.7	12.9	12.056
No. 3, minus 3 in.	52	7.3	14.7	3.872
No. 3, minus 2 in.	51	8.2	14.7	3.515
No. 3, minus 3/4 in.	40	9.3	14.7	3.952
No. 4, minus 3 in.	64	6.8	14.7	3.378
No. 4, minus 2 in.	61.5	7.4	14.7	3.230
No. 4, minus 3/4 in.	40	9.3	14.7	3.952

APPENDIX A: DETERMINING THE WATER CONTENT OF THE OVERSIZED FRACTION

1. This appendix describes a procedure for determining the water content of the oversized fraction of an earth-rock mixture for use in the following equation which is typically used for calculating the water content of a total material from that of a fraction or vice versa:

$$W_t = fW_f + cW_c \tag{A1}$$

or

$$W_f = \frac{W_t - cW_c}{f} \tag{A2}$$

where

W_t = water content of the total material, percent

W_f = water content of finer fraction, percent

W_c = water content of coarser (oversized) fraction, percent

f = percent by weight finer fraction expressed as a decimal

c = percent by weight coarser (oversized) fraction expressed as a decimal

2. In estimating the water content of the total material from that of a fraction, it has commonly been the practice to assume the water content of the oversized fraction W_c to be the absorption A of the gravel. Although not defined in EM 1110-2-1906, "Laboratory Soils Testing," (US Army Corps of Engineers 1970) the absorption A of a gravel is its water content in the saturated surface-dry condition. The saturated surface-dry condition is described in EM 1110-2-1906, Appendix IV: Specific Gravity and is that state where the surface of a gravel particle is essentially dry but where any tiny open voids or "pores" on the surface are filled with water. Although a rare case, the saturated surface-dry state would also include water filling any voids in the interior of a particle which may access water from the outside. The

absorption A may be calculated from the values of apparent and bulk specific gravities as follows:

$$A = \frac{G_a - G_m}{G_a G_m} \times 100 \text{ percent}$$

where

G_a = the apparent specific gravity of the gravel

G_m = the bulk specific gravity of the gravel

The absorption of a typical gravel which does not exhibit an abundance of tiny open voids in the surfaces of the particles or interior voids which can be filled with water is usually less than 5 percent.

3. There is no reason to believe that the gravel contained within a moist earth-rock mixture has a water content equal to the absorption. At partially saturated water contents near optimum, as is typical of fill placement water contents, it is likely that the water content of the gravel is somewhat less than the absorption. The presumption in using the absorption A in Equation A1 or A2 above is that the difference between the actual water content of the gravel and its absorption is too small to make a significant difference in the calculations especially since the water content of the gravel W_c is multiplied by the percent coarse (oversized) fraction c which is usually less than 50 percent.

4. The presumption that use of the absorption does not introduce significant error may or may not be true depending on the error as compared with the specified range in placement water content. For instance, if the total range in specified placement water content is three percentage points straddling optimum water content and the error introduced by use of the absorption is one percentage point, that is a very significant error. Even if the error introduced by use of the absorption is only 0.5 percentage points, it could be considered significant.

5. It is not prohibitive in time or expense to perform some simple testing to establish a general value for the water content of the oversized fraction as it actually exists in the total materials when those total materials are within the specified range in placement water content. The procedure is outlined as follows:

a. Obtain representative samples of the materials which include at least the gradations containing the most and least gravel and the largest and smallest maximum particle sizes. At least 250 lb of each sample should be obtained.

b. Spread each sample on a clean surface and air-dry the entire sample. Other means, such as ovens and heat lamps, may be used to accelerate drying if the maximum drying temperature is kept below 60° C.

c. Reduce all aggregates, or lumps formed during drying, of fine-grained material to particles finer than the No. 4 sieve. With a wire brush or other means, remove all fine-grained material that may be clinging to gravel sizes, taking care not to lose the fine-grained material.

d. Separate all the material into the finer fraction and the oversize fraction as will be defined in the fill compaction control procedure. This division will either be on the 3/4-in. sieve or the No. 4 sieve.

e. Weigh and determine the percent by total weight of oversize fraction and percent by total weight of finer fraction.

f. Recombine the two fractions, mixing thoroughly and taking care not to lose any of the material.

g. Add a sufficient weight of water to bring the total material to a water content approximately within the specified fill placement range. In calculating the quantity of water to add, consider the air-dry water content of the material to be one percent.

h. Thoroughly mix the added water into the sample. Place the wetted sample in sealed containers and determine the wet weight of the entire sample.

i. Allow the wetted sample to cure for at least 24 hr.

j. After the moist sample has cured, separate a sufficient portion of it over the sieve which defines the oversized/finer fractions to obtain a sufficient quantity of the finer fraction to determine its water content. Work out of the sealed container(s) as efficiently as possible taking appropriate measures to avoid drying of the materials during the extraction of the sample of the finer fraction. Be extremely careful not to lose any of the material.

k. Determine the water content of the specimen of finer fraction W_f obtained in j. above by oven-drying as per EM 1110-2-1906, Appendix 1 (US Army Corps of Engineers 1970). Retain the record of its wet W_{wf} and dry W_{df} weights.

l. Determine the wet W_{wr} and oven-dry W_{dr} weights of the remainder of the total sample. If oven size or capacity will not accommodate the entire remainder of the total sample, it may be dried in portions. Take care not to lose any of the material and keep the portions awaiting drying in a sealed container.

m. Calculate the water content of the total sample W_t as follows:

$$W_t = \frac{(W_{wf} - W_{df}) + (W_{wr} - W_{dr})}{W_{df} + W_{dr}} \times 100 \text{ percent}$$

n. Rearrange Equation A1 above to solve for the water content of the oversize fraction W_c as follows:

$$W_c = \frac{W_t - fW_f}{c} \tag{A3}$$

o. Substitute the following values into Equation A3:

(1) The percent finer fraction determined in step e. above expressed as a decimal.

(2) The percent oversized fraction determined in step e. above expressed as a decimal.

(3) The water content of the finer fraction W_f expressed as a percent determined in step i. above.

(4) The water content of the total sample W_t expressed as a percent determined from step k. above.

p. Solve Equation A3 for the water content of the oversized fraction W_c which will be in percent.

6. Note that the procedure above avoids the impractical task of separating the moist total sample into finer and oversized fractions such that no wet, fine-grained material adheres to the oversized fraction. It is this probability of adhering, wet, fine-grained material which negates a direct attempt to measure the water content of the oversized particles by simply oven-drying that fraction.

7. The above procedure applied to representative samples spanning the range in gradation of the earth-rock materials to be placed in the fill should yield a better general knowledge of the actual water content of the oversized material to be used with Equations 1 or 1a of the main report during the compaction control operations in the field.